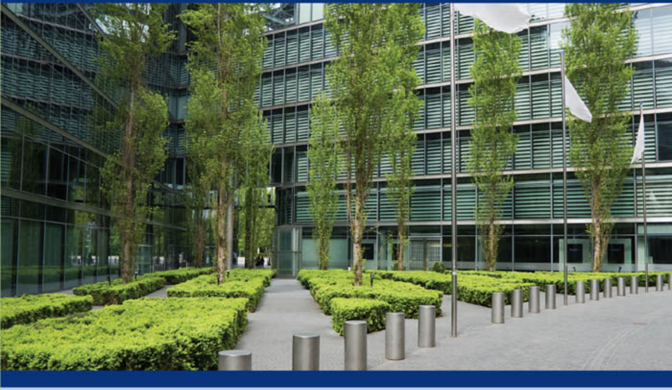
Low Impact Development Technology

DESIGN METHODS AND CASE STUDIES



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Low Impact Development Technology

Design Methods and Case Studies

SPONSORED BY

Low Impact Development Committee
of the Urban Water Resources Research Council
of the Environmental and Water Resources Institute
of the American Society of Civil Engineers

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Preface

Low Impact Development (LID) technology is rapidly become the standard for stormwater management in Federal, State and local jurisdictions throughout the United States and in many other countries throughout the world including; Australia, Canada, China, England, New Zealand, and Taiwan. As with many new and emerging technologies there is a learning curve associated with the application of the technology. The Low Impact Development Committee of the Urban Water Resources Research Council (UWRRC) of Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE) was formed to bridge this learning curve and facilitate the adoption of this new technology. One of the primary tools of the committee has been the sponsorship of s series of national and international conferences on LID technology which present the latest ideas and advances in the technology. One of these conferences was held in Philadelphia, Pennsylvania in September 2011.

The Philadelphia LID conference addressed a wide range of LID design topics and presented a number of case studies of LID applications. These topics have been organized and are presented in five individual chapters which include:

- LID Technology: Rain Gardens / Bioretention
- LID Technology: Green Streets & Hardscapes
- LID Technology: Green Roofs
- LID Technology: Design Methods
- LID Technology: Case Studies and Watershed Restoration

Other topics addressed in the Philadelphia LID conference included LID implementation and LID economics. These materials are presented in a companion volume, *Low Impact Development Technology: Implementation and Economics.*

Acknowledgments

The Philadelphia National LID conference and the proceedings of the conference could not have been possible without the dedicated efforts and leadership of the conference chairs: Dr. Robert Traver, Villanova University; Dr. Bill Hunt North Carolina State University; and Dr. Allen Davis, University of Maryland. In addition the outstanding efforts of Ms. Cathy Smith, Extension Associate of North Carolina State University are hereby acknowledged.

Many individuals were responsible for the success of the Conference. Our appreciation and gratitude are extended to the conference partners:

- US EPA
- Environmental & Water Resources Institute
- LID Center
- Water Environment Research Foundation
- Philadelphia Water Department - Office of Watersheds
- Temple-Villanova Sustainable Stormwater Initiative
- Temple University - Center for Sustainable Communities
- Center for Watershed Protection
- Chesapeake Stormwater Network

Our gratitude is also extended to the authors of the papers presented in this publication for their hard work and valuable contributions in the advancement of Lid technology.

We also extend our gratitude to the co-editors who donated their valuable time and intellect editing the technical papers presented in this publication. The co-editors include:

- Michael Clar, Ecosite, Inc., Ellicott City, MD
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Introduction

Low Impact Development (LID) technology is being increasingly adopted by Federal, State, and local government agencies as the preferred and sustainable approach to stormwater management associated with land development and redevelopment activities. Considering that this technology is only slightly over ten years old (e.g., the first LID Design Manual was published by Prince George's County, Maryland in 1998), it represents an unusually rapid rate of adoption for a new technology. This rapid adoption is due in part to the realization by local governments that the traditional approaches to stormwater management were not achieving the desired environmental protection goals, as well as the recognition that LID technology is based on ecologically sensitive and sustainable concepts that are essential and necessary to ensure that these environmental protection objectives are achieved.

The Philadelphia LID conference addressed a wide range of LID design topics and presented a number of case studies of LID applications. These topics have been organized and are presented in five individual chapters which include

- LID Technology: Rain Gardens / Bioretention.
- LID Technology: Green Streets & Hardscapes.
- LID Technology: Green Roofs.
- LID Technology: Design Methods.
- LID Technology: Case Studies and Watershed Restoration.

Rain Gardens / Bioretention

The rain garden / bioretention system remains the vanguard and workhorse of LID practices. This practice first develop for Prince George's County, Maryland (Clar, et al, 1993) has now become the most widely used and researched stormwater BMP practice in the world. While the two terms ar often used interchangeably, there is a growing trend to distinguish between them. The term rain garden is now increasingly being used to refer to a smaller structure requiring less formal design and reserved for use as an on lot residential practice. The drainage are to this practice is very small, typically 0.5 acre or less. At the same time bioretention is assigned to a larger structure requiring more formal design. The drainage area can range from 2 to 5 acres.

Six papers are presented in this group which address various aspects of rain garden/ bioretention design and performance. The paper by Ayers and Kangas, "Topsoil

Development in Bioretention Cells: What Are the Implications?" is rather unique. It represents the first published application of ecological engineering science to LID technology. The conclusions of this research which document the development on soil horizons in the bioretention profile and observation that an ecologically sustainable microcosm has developed in at least one or more of the observed sites has very significant implications for the life cycle of landscape based LID practices.

Green Streets and Hardscapes

Green streets and highways are rapidly gaining in popularity. First introduced in Portland, Oregon (Metro, 2002) and Seattle, Washington, (Tackett, 2007) the benefits and advantages of this concept have become recognized at the Federal, State and local transportation agencies. Four case studies are presented in the group which address a range of applications. The paper by Harper, "City of Richmond's Green Alleys Program" introduces useful details associated with the design of green alleys.

Green Roofs

Green roofs have become an important component of green infrastructure technology. Two papers are presented on this topic which address the removal of nitrates by green roofs and a review of the benefits and design features of tray systems.

Design Methods

Design methods and technology for LID applications are constantly developing. This group contains six papers which describes a wide range of design solutions and applications. The paper by Greer and Wright. "Estimating Annual runoff Based on NRCS Runoff Curve Number" provides an innovative attempt to integrate a single storm design concept imbedded in the NRCS approach with the time series data used for continuous simulation models such as,EPA's SWMM and Pitt's WINSLAM models.

Li et al., describe the "development of an LID Design Guide". Shamsi discusses modeling to quantify the benefits of LID for CSO reduction. Cheng offers a saturated seepage flow model for LID devices based on infiltration concepts. Ryan, et al. discuss the seasonal variations in transient storage induced by open canopies in urban streams. Lolcama, et al. describe hydrogeological testing, engineering and start-up of a gravity drain system.

Case Studies and Watershed Restoration

The final group of papers presents a number of case studies of LID applications. Gao and Sage examine the application of LID concepts for CSO watersheds. Bushey, et al. describe assessing the balance between stormwater and transportation for a developed LID neighborhood. MacDonagh describes the value of reforestation to meet stormwater goals. Cameron, et al. describe the objectives and cost considerations of green stormwater retrofits. Moses, et al. describe the coupling of stormflow attenuation and trail stabilization. Trinkaus and Hayden describe the retrofit of stormwater detention basins to enhance water quality.

Clar et al., 1993. Design Manual for Use of Bioretention in Stormwater Management. Prepared by Engineering Technologies Associates, Inc. (ETA) and Biohabitats, Inc., prepared for the Department of Environmental Resources, Prince George’s County, MD.

Metro, 2002. Green Streets, Innovative Solutions for Stormwater and Stream Crossings, Ist edition, Portland, OR

Tacket, Tracy, 2007. Natural Drainage Systems Design, Seattle Public Utilities, Seattle, WA

Impacts of Soil Texture, Structure, and Compaction on Bioinfiltration Device Performance: Results of Lab and Field Investigations

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Abstract

Biofiltration devices are a potentially effective option for the treatment and disposal of stormwater runoff from urban areas. However, the performance of these systems, and other infiltration devices, are affected by factors such as the texture, structure, and degree of compaction of the media during their construction. This paper presents the results of laboratory and field-scale studies conducted to provide insight on media characteristics of a poorly operating biofilter facility located in Tuscaloosa, AL. Double ring infiltrometer tests and soil compaction measurements were conducted along a large biofilter to determine the in-situ characteristics of the media. Infiltration measurements were also made during rain events for comparison to the results from the lab tests and the double-ring infiltration measurements. The effects of different compaction levels on the infiltration rates through the soil media were also examined during laboratory column tests, along with benefits associated with adding sand to the media mixture. The results indicated that soil compaction has dramatic effects on the infiltration rates; therefore care needs to be taken during stormwater treatment facilities' construction to minimize detrimental compaction effects. Adding sand to a media having large fractions of clay-sized particles helps minimize the detrimental effects of compaction on the infiltration rates also.

Introduction

The infiltration rate is the rate at which water enters the soil at the surface. Although infiltration may involve soil water movement in two or three dimensions, such as rainfall on a hillside, it is often treated as one dimensional vertical flow

(Skaggs and Khaleel, 1982). The infiltration of water into the surface soil is responsible for the largest abstraction (loss) of rainwater in natural areas (Pitt et al., 1999b). An understanding of the infiltration process and the factors that affect it is important not only in the determination of surface runoff but also in the subsurface movement and storage of water within a watershed (Skaggs and Khaleel, 1982).

The rate of infiltration depends on a number of factors, including the condition of the soil surface and its vegetative cover, the properties of the soil, such as its porosity and hydraulic conductivity, and the current moisture content of the soil (Chow et al., 1988). The infiltration rate in a soil typically decreases during periods of rainfall as the soil becomes saturated. Infiltration tests conducted on many different soils having a wide range of texture and representative of significant great soil and parent –material groups at 68 field sites representing 39 soil series and 6 of the great soil groups throughout the United States indicated that the infiltration rate decreases with increasing clay content and increases with increasing noncapillary porosity (Free et al., 1940).

Infiltration practices are becoming more common in many residential and other urban areas to compensate for the decreased natural infiltration areas associated with land development, but must consider local soil degradation conditions to be most effective (Pitt et al., 2002 and 2008). Infiltration facilities, which historically have included percolation ponds, dry wells, infiltration galleries, and swales, are designed to capture and retain runoff and allow it to infiltrate rather than to discharge directly to surface water (Massman, 2003). Properly designed and constructed infiltration facilities can be one of the most effective flow control (and water quality treatment) stormwater control practices, and should be encouraged where conditions are appropriate (Ecology, 2005).

Infiltration facilities have the greatest runoff reduction capabilities of any stormwater control practices and are suitable for use in residential and other urban areas where measured soil permeability rates exceed locally determined critical values (such as 1.3 cm/hr as specificed by VA DCR, 2010). However, the design of these facilities is particularly challenging because of the large uncertainties associated with predictions of both short-term and long-term infiltration rates (Massman, 2003). Premature clogging by silt is usually responsible for early failures of infiltration devices, although compaction (during either construction or use) is also a recognized problem (Pitt et al., 2002 and 2008).

Understanding the physical and hydrologic properties of different bioretention media mixtures as well as their response to compaction may increase the functional predictability of bioretention systems and thus improve their design (Pitt et al., 2002 and 2008; Thompson et al., 2008). The usual effects of soil compaction results in increased bulk densities, decreased moisture holding capacities, restricted root penetration, impeded water infiltration, and fewer macropore spaces needed for adequate aeration, all often leading to a significant reduction in infiltration (Gregory et al., 2006; Pitt et al., 2008; Thompson et al., 2008).

Substantial reductions in infiltration rates were noted due to soil compaction, especially for clayey soils, during prior research (Pitt et al., 1999b). Sandy soils are better able to withstand compaction, although their infiltration rates are still significantly reduced. Compaction was seen to have about the same effect as moisture saturation for clayey soils, with saturated and compacted clayey soils having very low effective infiltration rates (Pitt et al., 2008). Sandy soils can still provide substantial infiltration capacities, even when greatly compacted, in contrast to soils containing large amounts of clays that are very susceptible to compaction's detrimental effects. In a similar study that examined the effects of urban soil compaction on infiltration rates in north central Florida, Gregory et al. (2006) found a significant difference between the infiltration rates of a noncompacted pasture and wooded area, despite similar textural classification and mean bulk densities.

Soil amendments (such as organic composts) improve soil infiltration rates and water holding characteristics and add protection to groundwater resources, especially from heavy metal contamination in urban areas (Pitt et al., 1999a and 1999b). Groundwater contamination problems were noted more often in commercial and industrial areas that incorporated subsurface infiltration and less often in residential areas where infiltration occurred through surface soil (Pitt et al., 1999a and Clark et al., 2006). However, pretreatment of stormwater runoff before infiltration can reduce groundwater contamination of many pollutants and also prolong the life of the infiltration device.

Compost has significant pollutant sorption and ion exchange capacities that can also reduce groundwater contamination potential of the infiltrating water (Pitt et al., 1999b). However, newly placed compost amendments may cause increased nutrient discharges until the material is better stabilized (usually within a couple of years). In addition to flow control benefits, amended soils in urban lawns can also have the benefits of reduced fertilizer requirements and help control disease and pest infestation in plants (US EPA, 1997).

Infiltration Rate and Soil Density Measurements in Shelby Park Biofilter

The poorly operating biofilter facility selected for this study is about 90 m long and 9 m wide (810 m^2), and about 11% of the paved and roofed source area. It is located in Shelby Park, adjacent to the University of Alabama, Tuscaloosa, rental car parking lot, from which it receives flow. The drainage area and land use breakdown for the study area is shown in Table 1.

Table 1. Drainage Area and Land Use Breakdown

Drainage area	**Area(m^2)**	**Area(acre)**	**Land use** (percent)
Paved	6070	1.50	55.6
Landscape	3197	0.79	29.2
Roof	1660	0.41	15.2
Total	**10,927**	**2.70**	**100**

Turf-Tec Infiltrometers (Turf Tec, 1989) were used to measure the infiltration rates at 12 test locations along the biofilter. These small devices have an inner ring about 64 mm in diameter and an outer ring about 110 mm in diameter. The infiltrometers were gently driven into the surface of the biofilter soil (having poor vegetation cover) until the "saturn" ring was against the soil surface (Figure 1).

Figure 1. Double ring infiltration measurement installations and in-situ soil density measurement at Shelby Park biofilter.

Relatively flat areas were selected in the biofilter to install the Turf-Tec infiltrometers and small obstacles such as stones and twigs were removed. Three infiltrometers were inserted within about a meter from each other to measure the variability of the infiltration rates of the soil media in close proximity. Four clusters of three infiltrometer tests were conducted along the biofilter to examine variations along the biofilter length. The tests were conducted for a period of one to two hours, until the infiltration rate become constant. After the soil was inspected and sealed around each ring to make sure that it was even and smooth, clean water was poured into the inner ring and allowed to overflow and fill up the outer ring.

The rate of decline in the water level was measured by starting the timer immediately when the pointer reached the beginning of the depth scale. Additional water was added to both rings when the level in the inner ring dropped a measurable amount. The change in water level and elapsed time were recorded since the beginning of the first measurement. The measurements were taken every five minutes at the beginning of the test and less frequently as the test progressed until the rate of infiltration was considered constant. The infiltration rate was calculated from the rate of fall of the water level in the inner ring.

In-situ soil density measurements were also made in the same general locations of the infiltration measurements. A small hole, 15 cm deep and 15 cm wide, was hand dug very carefully to avoid disturbance of the soil that would bound the hole. The hole's side and bottom were also carefully smoothed. All of the soil excavated from each hole was placed into four separate Ziploc plastic bags to retain soil moisture. Sand was then poured into the hole from a graduated cylinder to measure the volume of the holes, up to the top of the soil that was removed from the biofilter. The excavated soil media was then transported to The University of Alabama environmental lab for further analyses. The soil media was weighed, dried at 105oC, and weighed again. The dry density and moisture content (percent) of the soil media collected from each test locations were determined. The density of the soil was determined by dividing the mass of oven-dried soil by the sand volume used to re-fill the hole. The soil moisture content (percent) was determined from the ratio of the mass of water to the mass of oven-dried soil media. The mass of water was obtained from the difference between the mass of the moist soil and the oven dried soil.

Samples of the soil were also analyzed by the soil laboratory at Auburn University. The biofilter media was classified as sandy clay loam, with 20% clay and 80% sand (3% organic matter content). The median size of the samples ranged from 300 to 3,000 um, and *in-situ* density measurements indicated surface dry density values of about 1.9 g/cc, corresponding to severely compacted conditions (close to "modified" compaction conditions for this soil). Poor vegetation growth also indicated compacted conditions.

Biofilter Surface Ponding

During rainfall events, if the runoff rate directed to the biofilter facility is greater than the infiltration capacity of the media in the biofilter, water will pond on the surface. Extended periods of surface ponding of water on the Shelby Park biofilter were often observed following heavy rainfall events (Figure 2).

Figure 2. Ponded water on the biofilter surface observed after rainfall event (the vegetation cover is very poor indicating likely serious compaction).

Infiltration rate measurements were manually recorded from biofilter ponded areas after five rainfall events between July 2010 and April 2011. Depth indicator rules were placed at 3 to 5 different locations in the biofilter at surface ponding areas. The decrease in the depth of water was measured every 30 min at the beginning of the observation period for each event, and less frequently as the test progressed, until the water completely infiltrated. The change in water level and elapsed time were recorded since the beginning of the first measurement. Measurements were taken only during the daylight hours and it was therefore difficult to accurately predict the total drainage time for some events. This method is time consuming, labor intensive, and greatly depends on operator care for accuracy, but was needed to verify the infiltrometer measurements using the Turf-Tec units during dry weather. These measurements were taken after the runoff ceased and the biofilter was fully saturated.

Laboratory Column Tests

The effects of different compaction levels on the infiltration rates through the biofilter soil media when mixed with varying amounts of filter sand were also examined during laboratory column experiments. A 100 mm diameter PVC pipe (Charlotte Pipe TrueFit 100 mm PVC Schedule 40 Foam-Core Pipe) purchased from a local building supply store in Tuscaloosa, AL was used to construct the columns for these tests. A total of nine columns, each 0.9 m long, were constructed as shown in Figure 3. The bottom of the columns had a fiberglass window screen secured to contain the media and were placed in funnels.

Figure 3. Laboratory column setup.

The columns were filled with about 5 cm of cleaned pea gravel purchased from a local supplier. The columns had various mixtures of media and filter sand added on top of the gravel layer. The filter sand was purchased from a local supplier in Tuscaloosa, Alabama. It has a median particle size (D_{50}) of about 0.7 mm and a uniformity coefficient (C_u) of 3. To separate the gravel layer from the media layer, a permeable fiberglass screen was placed over the gravel layer and then filled with the soil media imported from the biofilter, with varying amounts of added filter sand (soil media alone; 50 percent soil media and 50 percent filter sand; 75 percent soil media and 25 percent filter sand; 90 percent soil media and 10 percent filter sand). The media/sand layer was about 0.5 m thick.

Three levels of compaction were used to modify the density of the column media/sand samples during the tests: hand compaction, standard proctor compaction, and modified proctor compaction. Both standard and modified proctor compactions follow ASTM standard (D 1140-54). The standard proctor compaction hammer is 24.4 kN and has a drop height of 300 mm. The modified proctor hammer is 44.5 kN and has a drop height of 460 mm. For the standard proctor setup, the hammer is dropped on the test soil 25 times on each of three soil layers, while for the modified proctor test, the heavier hammer was also dropped 25 times, but on each of five soil layers. The modified proctor test therefore results in much more compacted soil, and usually reflects the most compacted soil observed in the field. The hand compaction is done by gently hand pressing the media/sand material to place it into the test cylinder with as little compaction as possible, with no voids or channels. The hand compacted soil specimens therefore have the least amount of compaction. The densities were directly determined by measuring the weights and volume of the media/sand material added to each column.

The infiltration through the biofilter media/sand was measured in each column using municipal tap water. The surface ponding depths in the columns ranged from 28 to 36 cm, corresponding to the approximate maximum ponding depth at the Shelby Park biofilter. The freeboard depth above the media to the top of the columns was about 50 to 75 mm. Infiltration rates in the media mixtures were determined by measuring the rates with time until apparent steady state rates were observed.

Results if In-Situ Biofilter Infiltration Measurements

The average initial infiltration rate using the double-ring infiltrometers was about 28 cm/hr, and ranged from 7.5 to 71 cm/hr. The final rates had an average value of about 12 cm/hr, and ranged from 4 to 27 cm/hr for the 12 tests (Table 2). However, measurements of the infiltration rates of the ponded water after actual rains indicated saturated rates of only about 1 cm/hr with little variation. At this location, the compaction of the biofilter media extended to the bottom of the excavated trench, with likely increasing compaction with depth due to the media placement methods. The small-scale surface infiltration measurements did not include sufficient water to saturate the system and only indicated more favorable surface conditions. Therefore, care needs to be taken when using any surface infiltration method when evaluating an infiltration facility having deeply placed media or excavations.

Table 2. Field Infiltration Tests

	Horton's parameters							
Test site location	**f_0(cm/hr)** mean	**f_0(cm/hr)** range	**f_c(cm/hr)** mean	**f_c(cm/hr)** Range	**k(1/min)** mean	**k(1/min)** range	dry density (g/cc)	moisture content (%)
1	16.5	(11.5-23)	5.1	(4-7.6)	0.07	(0.03-0.15)	2.2	9.2
2	42.1	(7.5-70.6)	15.4	(5.6-25.4)	0.07	(0.06-0.1)	2.3	5.6
3	31.7	(20.6-37.6)	11.4	(11.2-11.4)	0.09	(0.06-0.11)	1.8	8
4	22.8	(19-28)	15.2	(7.6-26.7)	0.045	(0.001-0.07)	2.1	8.2

A trench or borehole infiltration test would be more reliable in this case, or the preferred in-situ measurements with pressure transducer recording depth sensors during actual rains. These very low rates during the rains were about equal to the observed laboratory tests conducted under the most severe compaction conditions (the modified Proctor compaction tests).

Laboratory Infiltration Results

Biofilter media material obtained from the surface of the biofilter was brought to the laboratory for extended column testing. Figure 4 shows box and whisker plots of the different test conditions, comparing different compaction conditions with varying amounts of sand amendments (Table 3). The Coefficient of Variation (COV) of the laboratory infiltration rates through the biofilter media mixture ranged from 0.15 to 0.45.

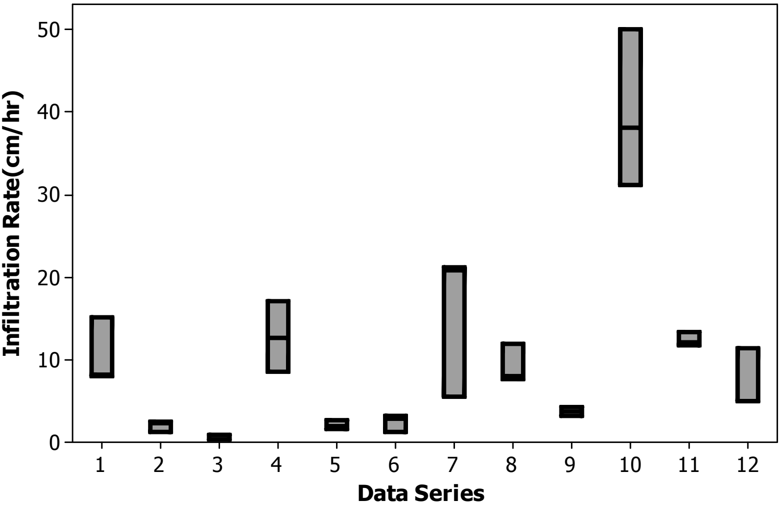

Figure 4. Box and Whisker Plots of the different test conditions, comparing different compaction conditions with varying amounts of sand amendments.

The plots indicate the major benefits by adding sand to the media material, even at only 10% for the most severely compacted material (infiltration increased from about 0.6 to 2.5 cm/hr), while the sand addition had less of a percentage increase benefit for the lightly compacted material at this low sand addition (from about 10.5 to 13 cm/hr). The percentage benefits were similar for all compaction conditions for the large sand additions (25 and 50% sand). The benefits of decreased compaction were much greater than the sand addition benefits. However, added sand prevented this very poor media material from complete failure, even with severe compaction (averaging at least about 2.5 cm/hr, with 10% sand, about 4 cm/hr, with 25% sand, and about 8 cm/hr, with 50% sand).

Table 3. Various Mixtures Of Media and Filter Sand Used For Laboratory Infiltration Measurements.

Data series	Compaction	percent (%) sand	percent (%) media
1	Hand	0	100
2	standard proctor	0	100
3	modified proctor	0	100
4	Hand	10	90
5	standard proctor	10	90
6	modified proctor	10	90
7	Hand	25	75
8	standard proctor	25	75
9	modified proctor	25	75
10	Hand	50	50
11	standard proctor	50	50
12	modified proctor	50	50

Conclusions

The laboratory column test results indicated that the infiltration rates through all mixtures of media and filter sand are greater than the infiltration rates through the biofilter soil media alone for the three levels of compaction (modified proctor, standard proctor and hand compaction). Mixing the biofilter media with filter sand improved the infiltration capacity of the media and also reduced the impact of compaction on the infiltration rates. The mixture containing 50% biofilter media and 50% filter sand exhibited the highest infiltration rates, as expected. The laboratory test results also demonstrated that soil compaction has dramatic effects on the infiltration rates; therefore care needs to be taken during the construction of biofilter stormwater treatment facilities to reduce detrimental compaction effects. The infiltration values from the ponded locations are very small compared to the laboratory and field test infiltration values, indicating fully saturated conditions and moderately to severely compacted conditions.

The in-situ infiltration measurements need to be evaluated cautiously. The ponded water measurements in the biofilter were obtained after complete saturation. Also, ponding was not even throughout the biofilter, and preferentially pooled in areas having depressions and with low infiltration capacities. Because they were in depressions, silting may have also occurred in those areas. Long-term and continuous monitoring in a biofilter during rains is the best indication of performance, and these spot checks likely indicate the lowest values to occur. In fact, they were similar to the lowest infiltration rates observed with the infiltrometers and also corresponded to the compacted media column tests. Data from the infiltrometers also need to be cautiously evaluated as they also show very high rates that only occur during the initial portion of the event. Most of the infiltration in biofilters likely occurs after saturated conditions and the lowest rates observed may be most representative of actual field conditions.

Acknowledgments

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Topsoil Development in Bioretention Cells
What are the Implications?

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Abstract

A newly constructed bioretention cell is like any other natural system; it can be expected to change over time as its ecosystem develops and establishes itself. Among these changes is the development of an enriched organic layer, or topsoil, at the soil surface, which is produced as plants grow and decay, and colonizing invertebrates and bacteria incorporate the resulting material into the soil. This enriched organic layer has properties significant to engineers, including increased porosity, increased cation exchange capacity, and increased bacterial activity. A field study was conducted to characterize the development of bioretention soils over time. A chronosequence consisting of ten bioretention cells of ages ranging from one to ten years was assembled. Parameters measured included: horizon depth, soil texture, soil organic matter, earthworm abundance and diversity, root biomass, and macroinvertebrate abundance and diversity. This study revealed a great deal of variation between sites in terms of their design and development, but also uncovered general trends that seem to apply universally. All sites were found to exhibit a characteristic soil profile in which soil organic matter and macro-biological activity decrease exponentially with depth. Earthworms were found at all sites, and their burrowing activity may play a key role in preventing clogging by solids deposition. The study reveals that biological activity is ubiquitous in bioretention soils, despite their location in isolated and degraded settings, such as parking lot islands. These findings may have significance for engineers, as they are likely to impact a bioretention cell's hydraulic and pollutant removal performance. Further research is needed to quantify these effects, and to explore the relationship between the emerging bioretention ecosystem and its encompassing urban ecosystem.

Introduction

Bioretention performance during a storm event depends on the hydraulic conductivity and pollutant removal capacity of the soil. These soil properties are influenced by the initial conditions of the constructed soil medium, including inorganic particle size distribution, organic additions, and vertical layering, as well as the actions of the plants, microbes and soil animals of the rain garden ecosystem. A bioretention soil begins as a mixture of topsoil, sand, and organic material. The proportions of these components vary by region and designer. Over several years, the colonization of the rain garden by diverse flora and fauna causes this medium to undergo a process of development of the soil profile common to all soils, which is known as pedogenesis. The first stage of pedogenesis is the development of organically and biologically enriched horizons at the soil surface. As this topsoil develops, it may change the soil's physical and chemical properties, and thereby affect performance. Thus, the development of bioretention soils over time must be examined if the long-term performance of bioretention is to be understood.

It is tempting to think of a bioretention cell as a sand filter with plants on it, but the acts of replacing the sand with soil and adding plants to the system lead to important differences in how the two technologies behave. By using a soil medium enriched with organic matter, providing shelter in the form of mulch, and a food source in the form of plants, a bioretention cell is transformed from an inert stormwater filter into a terrestrial ecosystem. A robust community of fauna will colonize the site over time. Each of the organisms present in this ecosystem inhabits a particular niche, and modifies its habitat through its metabolic activities. Plant litter falling on the soil surface is fragmented, inoculated with bacteria and fungi, and mixed into the soil by the actions of a community of macroinvertebrates. Bacteria and fungi complete the process of humification, converting this decayed plant material into stable humus.

As this soil ecosystem becomes established, organic matter begins to accumulate close to the soil surface, changing the soil's color and physical properties. The soil develops a characteristic black color due to the presence of dark-colored humic substances. Humus increases the water and nutrient holding capacity of the soil. Sticky organic substances, such as polysaccharides, are produced by a variety of soil organisms, including plant roots, mycorrhizae and bacteria. These organic substances cause soil particles to clump together into aggregates. These aggregates create a stable, porous soil structure. Soil aggregates are also formed in the guts of earthworms. Plant roots and macroinvertebrates such as earthworms create macropores, further increasing flow through the soil. Thus, it is biological activity that creates and maintains the permeability of the soil.

Analogs to pedogenesis in bioretention media may be found in the study of the regeneration of disturbed soils in ecosystems such as abandoned farmland and mine spoils. Scullion and Malik (2000) conducted a 9-year study of the influence of earthworms on soil development in coal mine spoils. They found that earthworm inputs increased the creation of stable soil aggregates. Hoogerkamp et al. (1983) inoculated abandoned pastures with earthworms, and observed the earthworms' effect on the soil profiles over a decade. They found that after about three years, earthworms had incorporated surface residues into the soil, and an A horizon had begun to develop. After nine years, the A horizon had increased in thickness to 5-8 cm. Roberts et al. (1988a, b) conducted experiments to compare pedogenesis on mine spoils topped with topsoil to those where the soils were amended with organic material. Within 1 year, A horizons were distinguishable in all plots. After three years, A horizons were more developed, and AC and C1 horizons were observable. A horizons were thicker in the topsoiled and organically-amended plots. Gonzalez-Sangregorio et al. (1991) observed organic carbon increases in lignite mine spoils over the first three years after restoration. These studies suggest that increases in organic matter near the soil surface should become evident within the first few years after rain garden construction.

When investigating processes occurring over long time periods, where direct observation of the development of a site or group of sites is difficult or impossible, natural scientists make use of chronosequences (Pickett, 1989). A chronosequence is a set of similar sites representing the development of a soil or ecosystem over time, with each site representing a different stage of development. Chronosequences are commonly used in the study of pedogenesis on disturbed sites (see e.g. Leisman 1957; Frouz et al. 2001).

An area of major concern in the long-term performance of bioretention cells is the potential that the soil surface will become clogged with sediment filtered out of captured stormwater runoff, and that this may lead to reduced infiltration rates (Li and Davis 2008a,b). Emerson and Traver (2008) conducted a four-year study of the hydrologic performance of a bioretention cell, finding seasonal variations in infiltration rate, but no evidence of clogging over time. The persistence of high infiltration rates may be attributable to the actions of the soil ecosystem. Soil macroinvertebrates, in particular earthworms, have been shown to increase soil porosity and infiltration rates (Bouche and Al-Addan 1997; Joschko et al. 1992). Earthworms achieve these increases by burrowing through the soil, mixing the soil, and by formation of aggregates through the mixing of soil particles with organic matter in their digestive systems. Even in very sandy soils, such as those used in bioretention, earthworms have been shown to form aggregates consisting of mineral soil particles fused together with organic matter (Shaw and Pawluck 1986). Earthworms have also been shown to reverse soil compaction (Ponder et al. 2000).

In addition to the maintenance of high infiltration rates, the soil ecosystem may have the potential to improve pollutant removal performance. Highly degraded organic matter in the form of humus has a very high cation exchange capacity, similar to silicate clays. As soil organic matter increases over time, this may improve the capacity of the bioretention soil to bind pollutants. In addition, growth of plant roots and their surrounding rhizospheres, combined with increasing macroinvertebrate activity, may boost bacterial populations, increasing degradation of organic pollutants and nutrient uptake (Brady and Weil 2002).

This research cataloged variations in soil characteristics between bioretention cells of different ages, with emphasis on soil ecosystem development. These data yield a chronosequence showing the development of biological activity and soil profiles over time. While comparison between research sites is complicated by differences in design and history, these data provide a valuable glimpse into processes working at a much larger time scale than are practical to study experimentally.

Materials and Methods

Ten existing bioretention cells were selected for assessment. They were selected to represent a wide range of ages and design styles, in order to get a sense of the spectrum of bioretention cells currently in use. The bioretention cells ranged in age from one year to ten years. All were located in the Washington, DC metro area, most in Prince George's County, Maryland. Table 1 shows the ages of each of the field sites.

Table 1. Age at sampling for each of the field sites

Site Name	**Site ID**	**Age at sampling (years)**
University of Maryland	UMCP	1
Washington Navy Yard	WNY	2
Mother Jones Elementary School	MJES	3
Chesapeake Bay Foundation	CBF	4
Northwestern High School	NWHS	5
Peppercorn Place	PP	5
Claggett Farm	CF	6
Chevy Chase Bank	CC	7
Beltway Plaza Mall	BP	7
Laurel Regional Hospital	LRH	10

Sampling was conducted during the summers of 2004 and 2005. Each site was sampled at three locations spaced evenly along a transect spanning the length of the bioretention cell. At each location, the litter layer was removed, and plants were clipped at the soil surface. A 20 cm x 30 cm hole was dug, and the first 10 cm of soil was removed. This material was hand sorted. Plant roots were collected. Earthworm lengths were recorded, and representatives were preserved for identification. Other macroscopic invertebrates were tallied and returned to the rain garden. Soil animals were classified into easily identifiable taxa. Approximately 1 liter of soil was removed for laboratory analysis. The procedure was repeated for the soil from 10-20 cm depth, and from 20-30 cm depth.

In the laboratory, plant roots were washed and oven-dried before weighing. Soil organic matter, SOM, was measured using the loss-on-ignition method (ASTM 2000). Earthworms were identified as completely as possible by external features.

Results and Discussion

The field surveys were intended to assess the extent of biological activity in the soil, to collect baseline soil physical data, and to look for evidence of pedogenesis in existing bioretention cells. Soil animals were found at all sites, with earthworms being the only soil animal to be observed at all sites. **Error! Reference source not found.** shows the richness, density, and diversity of the soil animal taxa found at each site. Taxa richness is represented by the number of different taxa collected. Density is represented by the number of individuals of all macroinvertebrate taxa collected at each site. Diversity was evaluated using the Shannon Index, $\bar{H}$, calculated as follows:

$$\bar{H} = -\sum P_i \log P_i$$

where P_i is the proportion of the individuals tallied belonging to the ith taxon (Odum and Barrett 2005). Higher values indicate a greater number of taxa observed at a higher degree of evenness in density between taxa. Sites with a high degree of diversity, such as CBF, NWHS, PP, and CC, are developing the most robust and complex ecosystems. Further study is required to quantify the influence of age, vegetation, and management on macroinvertebrate diversity, and to evaluate which performance metrics may be associated with high diversity.

Table 2. Macroinvertebrate diversity in each of the sampled bioretention cells

	Richness	**Density**	**Diversity**
Site ID	**Number of taxa collected**	**Number of individuals collected**	**Shannon Index**
UMCP	5	21	1.19
WNY	2	41	0.68
MJES	11	235	1.38
CBF	10	140	1.63
NWHS	11	169	1.59
PP	9	67	1.54
CF	10	210	1.16
CC	12	161	1.52
BP	6	67	0.88
LRH	10	81	0.91

When treated as a chronosequence, the ten field sites yield a picture of the development of a bioretention cell over a decade. In these first ten years, we see the beginnings of pedogenesis, with the gradual formation of an A horizon, enriched with organic matter. **Error! Reference source not found.** shows the gradual development of an enriched organic layer in the uppermost soil layer (0-10 cm) over time. The profiles show both a shift toward higher organic matter in the upper layer and a shift toward a steeper gradient of organic matter between the upper and lower soil layers.

Root biomass increases as plants become established; therefore root biomass is expected to increase over the first years after planting. **Error! Reference source not found.** reveals a shift to the right with the age of the bioretention cell. The diagram shows the gradual formation of a gradient with depth, with the greatest root biomass in the topsoil, and decreasing at deeper soil levels. This is an expected result, corresponding to declining oxygen levels at greater soil depths. The trend toward increasing root biomass with age is not monotonic, but the data suggest that older bioretention cells tend to have greater root biomass than do younger bioretention cells.

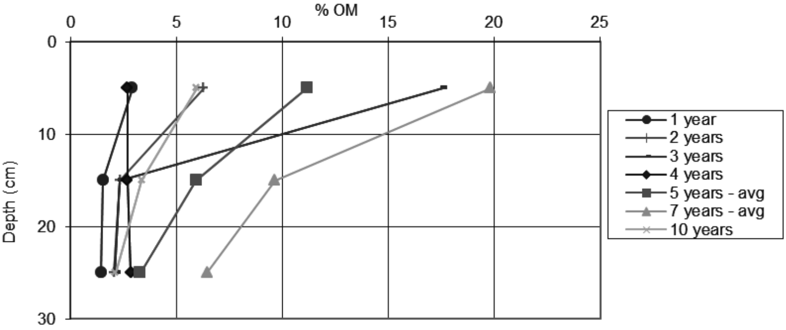

Figure 1. Soil organic matter depth profile for sampled chronosequence

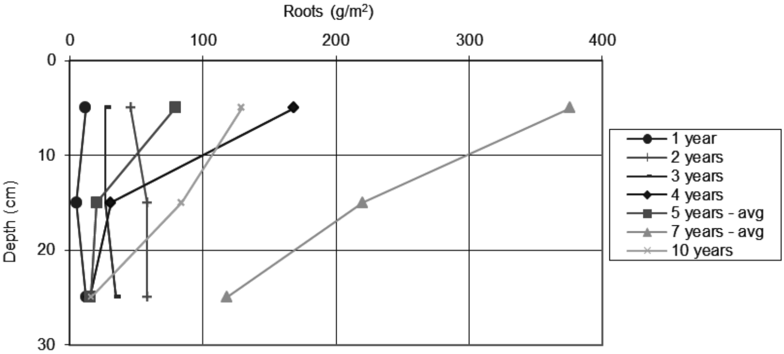

Figure 2. Root biomass depth profile for sampled chronosequence

Error! Reference source not found. suggests an increase in earthworm abundance over time at all depths, with greater increases in the uppermost soil layer. This is consistent with the gradual colonization of the sites by earthworms washed in from surrounding natural areas. Note that the 3-year-old site, MJES, had many more earthworms than any of the other sites. The reason for this is unclear.

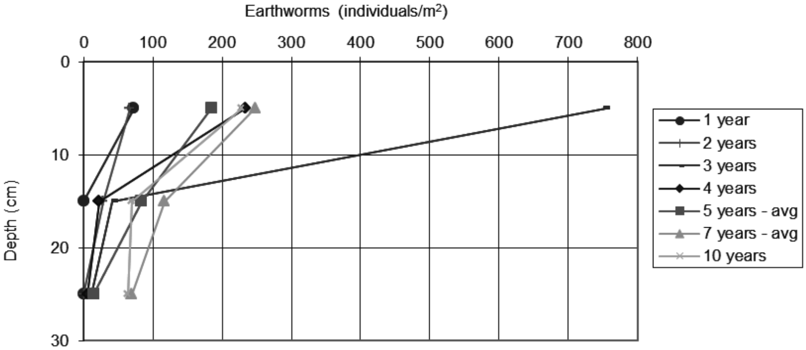

Figure 3. Earthworm abundance depth profile for sampled chronosequence

Variations in the histories of these sites make them an imperfect chronosequence. They differ in many respects, some of which may influence organic matter, root biomass, and animal populations to a greater degree than the passage of time. The most important of these factors are: variations in soil texture, differences in plant cover, differences in the litter/mulch layer, and variations in the proximity to natural areas. Stevens and Walker (1970) contend that all chronosequence studies fail in one way or another to control for all soil forming factors apart from time, but assert that even flawed chronosequences can be useful for making qualitative comparisons.

Sampling of soil-dwelling macroinvertebrates is notoriously difficult to perform accurately (Southwood and Henderson, 2000). A number of factors could have influenced the survey results. Environmental factors, such as time of year, temperature on the sampling date, and the antecedent weather conditions, may have influenced macroinvertebrate populations at the time of sampling. In addition, the sampling method used, while appropriate for assessing the earthworm population, does not give an accurate population estimate for all taxa. Many of the very small soil animals, such as springtails, were probably missed during hand sorting. For this reason, animal numbers should be used only for comparison between these sites and not for comparison with other studies. Many soil animals are likely to have escaped during the sampling process.

Conclusions

Understanding the performance of bioretention cells over time requires consideration of the influence of the soil ecosystem on its physical and chemical properties. Once installed, a bioretention cell's soil develops in a manner similar to a degraded soil in any other setting. That is, plants and soil animals colonize the soil, and systematically change the soil structure. This survey has confirmed that soil-dwelling macroinvertebrates are ubiquitous in bioretention cells, in spite of their physical isolation. In particular, earthworms were found at all sites, and had colonized the sites within a year of construction. The field surveys show a clear development of a characteristic soil profile with exponentially decreasing soil organic matter and biological activity with depth. In this way, bioretention cells self-organize from a planted depression filled with a simple mixture of topsoil, sand and organic material into a complex ecosystem.

These changes in the soil profile may impact the performance of the bioretention cell, both in terms of hydraulic conductivity and pollutant removal.

Figure 4 shows a conceptual model of how biotic and abiotic factors may interact within a bioretention cell, ultimately impacting the cell's drawdown time. These interactions need to be explored more deeply in order to fully understand how bioretention cells behave over time.

Engineering a living system is a challenging task, requiring an understanding of both the physical requirements to be met and the ways in which the system will behave and evolve over time. This study is an attempt to integrate ecology and soil science with civil engineering. Bioretention cells are a new kind of ecosystem, and are not yet well understood. Revealing the functioning of the bioretention ecosystem will necessarily be an iterative process, with each new discovery raising new questions.

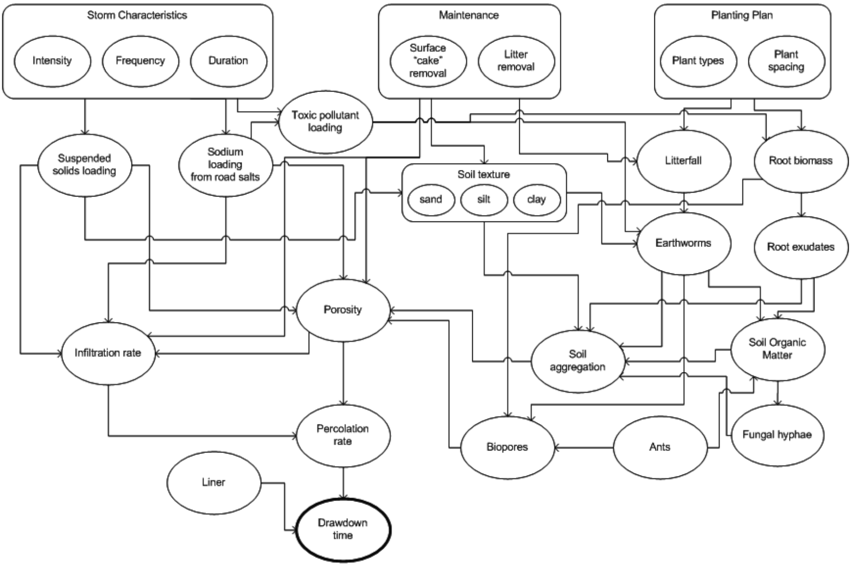

Figure 4. Biotic and abiotic factors influencing the drawdown time of a bioretention cell.

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The BMP That Keeps on Giving: Quantifying the Impact of Native Plants on Soil Water Properties

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Abstract

In this paper we demonstrate that in the upper soil column, vegetation type and cultivation practices can have as much of an influence on soil moisture retention and infiltration as soil texture class. First, we show that better a priori estimates of infiltration for natural and naturalized areas can be derived using soil data from natural landscapes rather than from cultivated areas. Our infiltration estimates, derived from German forest soil water retention data (Teepe, et.al., 2003), compare significantly better to measured data from natural/naturalized sites than estimates derived from widely used USDA models. We also applied the DRAINMOD water balance model to compare drainage and runoff characteristics of the same soil for suburban lawn and adjacent mixed pine and hardwood forest on a site in Raleigh, North Carolina. For DRAINMOD inputs, lawn soil moisture and saturated hydraulic conductivity were estimated using the USDA model while the forest soil properties were estimated using the Teepe adjustments. Long-term continuous model results show that for the same soil, without accounting for any interception losses, the average annual runoff was 0.14 inches and 9.1 inches for the forest and lawn areas respectively.

Introduction

Plant roots and their associated microbes have co-evolved with soils to play a significant role in soil formation processes through a wide range of physical, chemical and biological processes (Hinsinger, et.al., 2009). The rooting zone is known as the rhizosphere and is defined as the volume of soil around living roots, either in direct contact with the roots or within several millimeters of the root surface. Much of the biological activity in this zone is fueled by plant exudates, the chemical byproducts of photosynthesis that "leak" out of plant roots. Plant exudates include carbohydrates, sugars and proteins that fuel the growth of bacteria and fungi, which in turn are fed upon by nematodes and protozoa and so on, up the food chain.

Soil provides a torturous pathway for water movement with numerous constrictions or "necks" and occasional dead ends. While it is difficult to describe flow on the microscopic level, it is made even more daunting given that a healthy rhizosphere is an actively growing ecosystem. Scientists and engineers typically resort to a description of flow as the average of all microscopic flow paths over a defined volume of soil. This has led to Darcy's Law, where groundwater flow is held to be proportional to the energy gradient, and the proportionality constant, K, is called hydraulic conductivity.

Hydraulic conductivity is considered a function of the porous medium, its total porosity, distribution of pore sizes and pore connectivity/tortuosity as well as the fluid's properties, including density and viscosity. The porous medium's contribution to hydraulic conductivity is called the intrinsic permeability and can be estimated as a function of the material grain size. However, in the rhizosphere the physical architecture of the soil is as much dictated by the structure of inorganic soil particle packing as it is by the impact of biological processes.

Cultivated vs Natural/Naturalized Soils

For the purposes of this paper vegetated landscapes are broadly categorized here as either cultivated or natural/naturalized. Cultivated landscapes serve specific human needs – food production in the case of agricultural land and certain, less-well defined social and cultural purposes for cultivated lawns. The natural or naturalized landscape data we have compiled are primarily from temperate climates and include conserved or restored forests and prairies, as well as specific planted areas that utilize some combination of native plants to reduce runoff, flooding, erosion or nutrient losses, e.g. USDA Conservation Reserve Program (CRP) land.

Two of the main differences between cultivated and natural/naturalized areas that matter to soil water properties are vegetation type and the means of cultivation. The aim of most cultivation in the United States is the maximization of monoculture productivity, whether that monoculture is corn or soybeans or turf grass. The means of production for these crops entails either annual planting or intensively managing a perennial crop. Cultivated land is typically compacted by mechanical equipment and/or human and domesticated animal foot traffic. The maximization of the monoculture crop also usually entails intensive water, herbicide, pesticide and nutrient inputs.

These specific cultivation regimes mostly ignore rhizosphere ecology. Root growth is limited by growing annuals or by regularly trimming perennials. For instance, the more grass is cut, the more the shoots will utilize available carbohydrates at the expense of the roots. Keeping grass short keeps the roots short and at a greater risk of succumbing to disease, pests or climate extremes (DiPaola and Beard, 1980). The typical inputs for domestic monocultures include inorganic fertilizers, herbicides and pesticides that can significantly reduce biological diversity in the rhizosphere. This regime results in a stunted rhizosphere, poor soil structure, and a high susceptibility to compaction.

Root growth directly impacts soil structure through changes in packing and density as well as the creation of new porosity and connectivity of porosity. Researchers, such as Feeney, et.al., (2006) have shown that not only is there an increase in porosity due to biological activity, but the correlation of the pore space also increases; that is, the pore architecture changes from a random distribution to a more ordered, correlated structure. This leads to an increase in local diffusion rates and higher resource allocation to the microsites where the microbial populations reside.

Well-vegetated soil is permeated by biological structures – live and dead roots, worm holes, insect burrows, mycorrhizae fungi, soil aggregates and so on. This biologically-related structure contributes to the growth of macropore flow paths that can dominate the movement of water through soils. Some researchers think of soil in terms of two-domains – the first described by Darcy flow – a regular medium where flow is assumed to move at an average rate and the second domain – macroporous or preferential flow, where individual pores have their own specific flow and velocity fields.

Soil Water Characteristics

Soil structure, pore size distribution and hydraulic conductivity can all be inferred from the soil water retention curve (Hillel, 1982). The soil water retention curve is derived experimentally by applying varying degrees of suction (or vacuum) to a saturated soil column and determining the relative amount of water retained by the soil versus the water released for each suction value.

The force with which the soil "holds onto" water is measured in terms of matric (soil matrix) potential, or matric suction. It can be thought of as the magnitude of suction needed to "pull" water from the soil and break the surface tension between the water and soil surfaces. By convention this suction is typically expressed as a positive pressure. A matric potential of zero means the soil is completely saturated and water is freely available. As a soil dries out, it takes more suction to break the attraction between the soil and water. At varying thresholds for different soils and plants, the suction needed to break this bond exceeds the plant's "suction" capacity. This is called the permanent wilting point (PWP), the point beyond which a plant cannot pull enough water from the soil to sustain growth.

At relatively low matric suctions, e.g. between 0 and 100 KPa, most of the water removed is from the large macropores. Water is retained in smaller pores mostly due to the capillary effect (a combination of surface tension in the water and its adhesion to pore walls) and mostly as a function of soil structure. At higher suctions, as smaller and smaller pores empty out, the water retained is due more to water adsorption and is influenced less by soil structure and more by soil texture and specific surface properties. Hillel (1982) notes that there is a strong correlation between a suction of 1,500 KPa, often taken to be the lower limit of moisture availability to plants (PWP), and the surface area of a soil. At this suction there is only enough water for a thin coating over soil particle surfaces, but still enough to sustain microbial life.

Developing a soil water retention curve is a time-consuming test procedure. Pedotransfer functions (PTFs) are functional relationships that can be used to "transfer" or convert readily available soil properties, such as soil texture and organic matter content into hard to measure properties such as soil water retention and infiltration. The Green-Ampt infiltration equation parameters of Rawls, et.al., (1982) were derived from a PTF that is based on multiple regressions of clay, silt, sand and organic matter fractions. Saxton and Rawls (2006) refined these relationships and created a soil-water characteristics program for the USDA Soil-Plant-Air Water (SPAW) field and pond hydrology model. SPAW estimates bulk density, the soil water retention curve and hydraulic conductivity from user-specified sand, silt, clay and organic matter contents, along with minor corrections for compaction and salinity. Saxton and Rawls used their soil water retention relationships to derive an expression for saturated hydraulic conductivity (K_{sat}) that is a power function of moisture held at low suctions (see **Equation 1** below).

$$K_{Sat} = 1930(\theta_S - \theta_{33})^{(3-\lambda)}$$

$$\lambda = \frac{1}{B}$$

$$B = [\ln(1500) - \ln(33)]/[\ln(\theta_1 33) - \ln(\theta_1 1500)$$

Where ;

$\theta_S, \theta_{33}, \theta_{1500}$ are the water contents of the soil at S = saturation,
33 = -33 KPa suction and
1,500 = -1,500 KPa matric suction, respectively.

This equation depends primarily on the change in soil moisture between saturation and 3.33 KPa. This is the difference in soil water content between saturation and field capacity, where field capacity is the water content of a soil after all water that can freely drain via gravity, has drained away. The soil volumes first drained tend to be the macropores, interaggregate spaces and preferential flow paths.

The original PTFs of Rawls, et.al., (1982) were published by the US Soil Conservation Service in the Transactions of the American Society of Agricultural Engineers. That work was originally provided mainly as a service to the agricultural community. Rawls, et.al., purposefully excluded soil samples that had a high organic matter content and/or low bulk density because these properties were deemed unrepresentative of the primarily agricultural land they were interested in describing.

Conversely, we went looking specifically for soils data from natural/naturalized areas. These soils tend to have high organic matter contents and low bulk densities. The data we compiled were limited to the upper soil horizons, usually just the A-horizon, at depths between 0 – 10 cm or 0 – 30 cm. Several dozen studies were compiled for use in this analysis. For the sake of space, most of the studies used here are not cited in the reference list at the end of this article. The entire reference list is available upon request from the author.

We revised the SPAW PTFs using the soil water retention curves developed by Teepe, et.al., (2003) at the Institute of Soil Science and Forest Nutrition at the University of Gottingen, Germany. Teepe, et.al., set out to rectify the German practice of using agricultural soils data from the German Soil Survey (AG Brodenkunde, 1994) to specify soil water properties for forest soils. They developed water retention curves for 1,500 German forest soil samples and related them to soil texture, bulk density, and carbon content. They developed soil moisture retention curves for each German soil texture class and divided up each class into four bulk density groups: < 1 gram per cubic centimeter (g/cc); between 1 g/cc and 1.25 g/cc; between 1.25 g/cc and 1.45 g/cc and >1.45 g/cc.

We used the Teepe soil water retention curves by texture class-bulk density group to re-calculate K_{sat} with the Rawls' equation (**Eq.1** above) for the natural/naturalized soils data sets we collected. We compared our results to estimates of K_{sat} derived from the SPAW program for the same data sets (See **Figure 1**). The estimated values using the Teepe water retention curves match the range, variation and averages of the data better than the original Saxton-Rawls function (Saxton-Rawls $r^2 = 0.075$; Teepe $r^2 = 0.49$). Because our Teepe estimates are developed for each soil texture – bulk density class and given that most of the soils in the collected studies are silt loams, the Teepe estimates fall mostly onto three large groups on the figure.

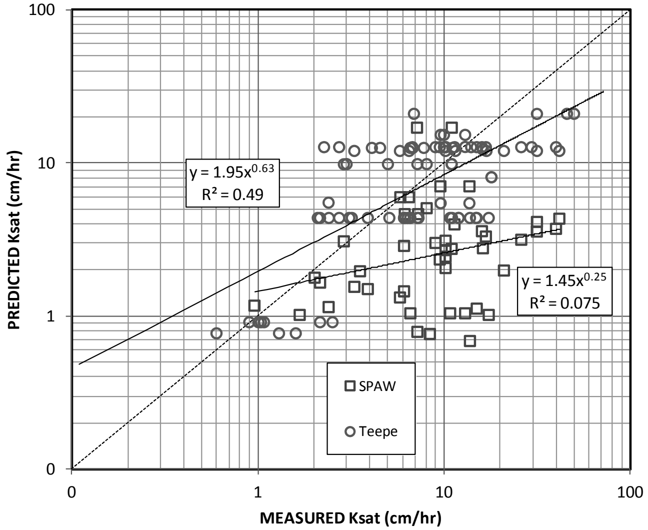

Figure 1. Data vs SPAW & Teepe-Corrected Estimates of K_{sat} for Prairie, Forest and CRP

We found that SPAW does a better job predicting K_{sat} for cultivated land ($r^2 = 0.33$) than for natural/naturalized areas ($r^2 = 0.075$). SPAW significantly under-predicts K_{sat} for natural/naturalized areas and that under-prediction is roughly the same order as the differences between K_{sat} measured on adjacent cultivated and natural/naturalized areas. On average, the measured K_{sat} for the same soil is roughly four to ten times higher for natural/naturalized areas than for immediately adjacent cultivated areas. In some cases, particularly for prairie remnants, the measured infiltration rates are nearly 20 to 40 times higher than the measured rate for adjacent cultivated land composed of the same soil.

Comparison of Lawn and Forest Soil Hydrology

We compared the infiltration, evapotranspiration and runoff of the same soil underlying a young lawn and an immediately adjacent 40-year old mixed pine - hardwood forest in the Piedmont province of North Carolina. Using data from a dissertation completed at North Carolina State University (Kays, 1979), we developed the respective soil water retention curves and hydraulic conductivities for the lawn and forest areas from a new housing development (Sudbury) in Raleigh, NC. We used the SPAW PTF relationships for the lawn soils and the Teepe-adjusted relationships for the forest soils. **Table 1** below summarizes the data and model-derived values for both land covers. Using these soil properties, and a long-term climate data set (1938-2004) we ran a continuous simulation of soil moisture using DRAINMOD.

Table 1. Sudbury Soil Characteristics (site data from Kays, 1979).

	Field-Measured Data							Estimated Values	
	Depth (cm)	Horizon	Texture Class	Bulk Density (g/cm^3)	Total Porosity cm^3/cm^3	Organic Matter (%)	Measured Ksat (cm/hr)	SPAW Ksat (cm/hr)	Teepe Ksat (cm/hr)
LAWN	0-8	A	Sandy Loam	1.349	0.492	2.9	0.7	1.37	NA
	8-20	B1	Sandy Clay Loam			2.1		0.53	NA
	20-35	B21t	Clay	1.594	0.399	0.8	0	0.01	NA
	35-70	B22t				0.9		0.004	NA
FOREST	0-5	A	Loam	0.957	0.639	8.3	31.56	2.82	20.9
	5-12	B1	Loam			4.3		0.89	12.67
	12-35	B21t	Clay	1.387	0.477	1.6	17.47	0.05	0.05
	35-85	B22t				1.5		0.03	

DRAINMOD is a long-term, field-scale, continuous simulation freeware program that was originally developed in the 1970s at North Carolina State University to model agricultural drainage systems. The model has remained in active use since that time and has undergone several revisions in order to analyze subsurface drainage for wetland systems, frozen soils and nutrient transport.

The model uses approximate relationships developed from soil water characteristics and saturated and unsaturated hydraulic conductivity to simulate the storage and redistribution of water in the soil profile. The model simulates the effects of various water management scenarios, such as surface and subsurface drainage and irrigation as well as crop production on the water table by performing a one-dimensional water balance. The water balance accounts for irrigation, precipitation, runoff, evapotranspiration (ET), drainage systems as well as lateral and vertical seepage.

The climate data set is from the Southwest Research and Outreach Center in Lamberton, Minnesota and is one of the climate data sets supplied with the DRAINMOD model files. The data includes hourly precipitation and the daily mean, maximum and minimum temperatures. As this is a relative comparison of the impact of plants on soil water properties, the fact that the soil and climate data are from different regions does not have a bearing on the intent of this analysis.

The data in Table 1 summarize the key differences between the soils. Although there are slight differences in the texture classes, these areas have the same soil (Typic Hapludult, Clayey, Kaolinthic, Thermic, Cecil Series). All the forest soil horizons show significantly higher organic matter (OM) content, total porosity and measured saturated hydraulic conductivity (K_{sat}) than the lawn soil. The K_{sat} measurements were done with a constant head, double ring infiltrometer and each infiltration measurement was taken when the infiltration rate stabilized after at least 60 minutes of flooding the soils.

The most distinctive feature of the water retention curves is the high saturated water content (total porosity) of the upper soil horizons in the forest. The A-horizon, in particular, has an extremely high saturated water content. Recall that the water content drained between saturation and field capacity (approximately 33 Kpa) represents water drained away by gravity typically via marcopores and/or preferential flow paths. The impact of these preferential flow paths on infiltration and soil draining is disproportionate to their overall contribution to total soil porosity. In addition, the distribution, size and flow paths of these preferential flow routes probably also contributes to the wide variability of infiltration that can be encountered in the field, particularly for natural or naturalized landscapes.

For our simulation, we set DRAINMOD's drain tile coefficient equal to zero to eliminate any loss through drain tile flows. We entered the lawn and forest soil moisture retention curves in DRAINMOD's SOILPREP sub-routine to develop the drained-volume, water table depth, upward flux relationships and Green-Ampt infiltration parameters for each soil type. We also set the deep vertical seepage component to a modest 0.0025 cm/hr and assumed an initial water table depth at 150 cm below the ground surface.

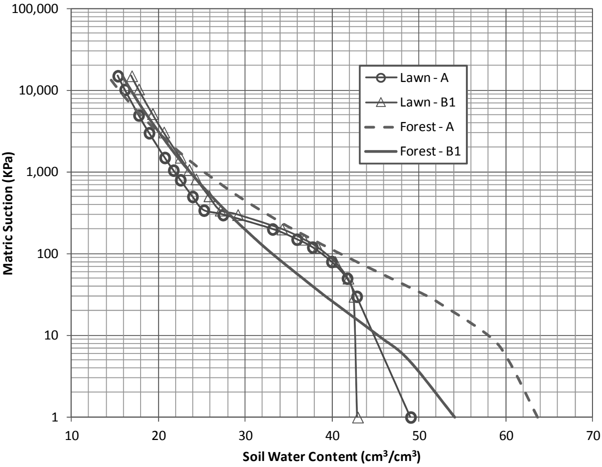

Figure 2. Sudbury soil moisture retention curves derived from data and SPAW (lawn) and Teepe-corrected (forest) pedotransfer functions for A and B1 soil horizons

DRAINMOD also allows for the user to set the rooting depth of the simulation "crop". This rooting depth allows for ET losses to occur not only near the surface of the soil, but also provides the plant the capacity to withdraw soil water below the rooting depth down to the permanent wilting point of soil moisture in the column (assumed to be a matric suction of 1,500 KPa).

DRAINMOD Results

For Figure 3 we have pulled out the model estimates of dynamic water table depths for the year 1995 from the continuous 67-year model run. The figure shows the water table depth for the lawn and for the forest soils assuming they have the same rooting depth (assumed depth = 7 cm) and assuming a forest rooting depth of 75 cm. This deeper forest rooting depth is probably still conservative.

The smaller the soil moisture storage capacity the faster that capacity is used up during rain events and the faster the upper soil column drains out. Organic matter helps soil "hold onto" water longer. Soils with high OM contents not only tend to have a higher field capacity, but also hold onto water more forcefully at suctions above field capacity. That water is bound to the organic – inorganic soil matrix but is still available to plants and microbes. So while water typically infiltrates through these organic soils more quickly, there is also more overall storage of water that is plant-available for longer. When the plant roots are simulated down to a depth of 75-cm, the average water table depth is lower (refer to **Figure 3**) – these deeper roots are pulling water from deeper in the column.

Another aspect of the rhizosphere that is not expanded upon here is that deep-rooted tree and native prairie plant roots have the capacity to grow down through clay layers. In their endless search for resources, particularly water, these roots can reach down through clay and can provide routes for water to move through what was previously an aquitard or aquaclude. This effect is convincingly documented in Selbig and Balster's (2010) comparison of Madison, Wisconsin rain gardens planted with turf grass and prairie plants.

When played out over the entire 67-year simulation, the difference in runoff generation between these lawn and turf sties is significant (see **Figure 4**). The forest soils only generate runoff for three out of 67 years, with an average annual runoff of 0.14 cm. These runoff events are rare occurrences and require significant rain events to occur in rapid succession in order to use up all the soil storage space and "keep ahead" of infiltration and ET losses. The lawn, on the other hand, tends to generate some runoff almost every year and had an average annual runoff of 9.1 cm. The average annual rainfall over the simulation is 116 cm which is equal to the average, annual forest infiltration loss. The average annual infiltration for the lawn is 107 cm. The average annual ET losses are 95 cm and 60 cm for the forest and lawn respectively. The lawn runoff losses get as high as 25% of the total rainfall in any given year, even though the upper soil horizons can be considered well-draining. Note that this simulation did not account for interception losses, which have been shown to be on the order of 10% to 50% of the annual rainfall for forests (Crockford and Richardson, 2000).

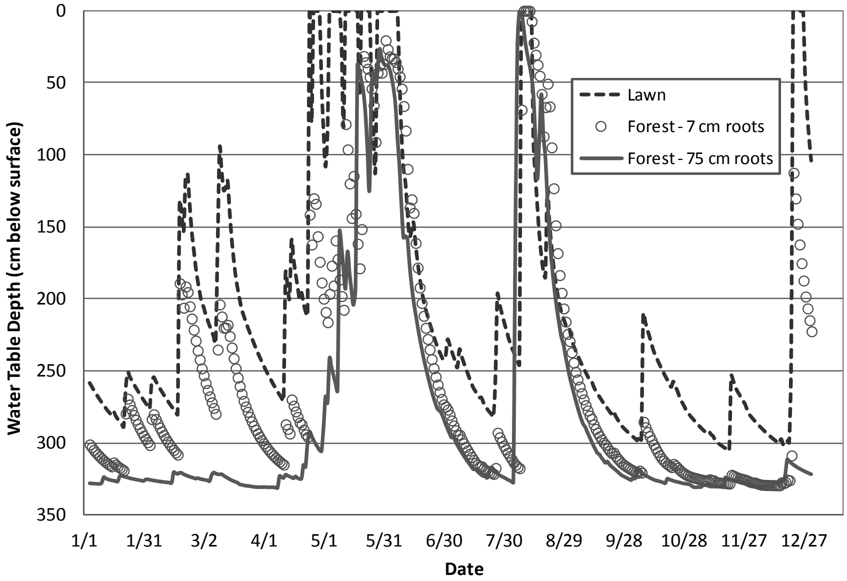

Figure 3. DRAINMOD-Estimated Water Table Depths at Sudbury Lawn and Forest Sites for the Year 1995

Conclusions

It bears repeating: these contrasted data sets are from the same inorganic soils, derived from the same combination of geology and climate. But they behave very differently depending on the type of vegetation cover and how intensively it is managed. In typical cultivation schemes, our end point is usually maximizing single crop production. Natural (or naturalized) landscapes tend to maximize total ecosystem production. When ecosystem production is overwhelmed by one species, that is usually an indication of an ecosystem imbalance. Ecosystem production depends on a web of inter-related species and processes that have co-evolved over millions of years. This process has led to highly resilient systems.

We have looked at just one set of outcomes for "allowing" or selecting for a more natural/naturalized landscape: the creation of more "generous" soil water and stormwater management properties. This is just one among many benefits that accrue from choosing to cultivate diverse ecosystems over monoculture crops. Among other benefits, healthy plant-rhizosphere ecosystems sequester carbon; filter and transform pollutants, build soil quality and retain valuable, sustainable biodiversity for plant and animal life.

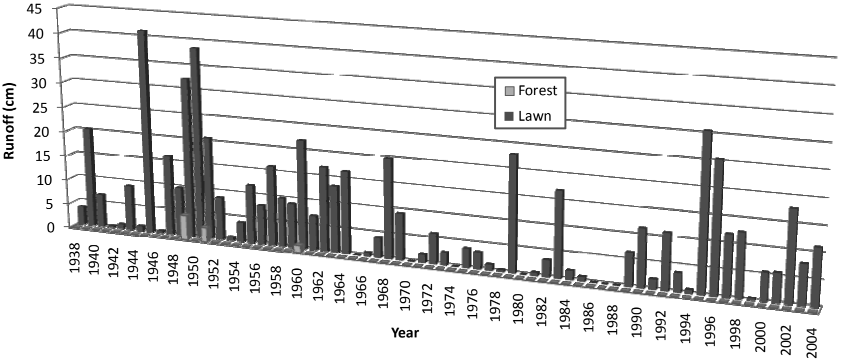

Figure 4. Annual DRAINMOD Runoff Totals for Sudbury Forest and Lawn 1938-2004

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Effect of Vegetation on the Fate of Petroleum Hydrocarbons in Laboratory-Scale Raingardens

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Abstract

Little is known about the ultimate fate of petroleum hydrocarbons in bioretention areas or the factors that influence their fate, including vegetation choice. In this work, laboratory-scale bioretention cells were constructed inside sealed glass columns and spiked with ^{14}C-naphthalene to permit an accurate accounting of naphthalene fate. Three columns were operated for approximately 5 months: an unplanted control column, a column planted with Blue Joint Grass, and a column planted with purple prairie clover (a legume). Naphthalene volatilization, leaching, biodegradation (mineralization), sorption, and plant uptake were determined. Adsorption to soil was the dominant naphthalene removal mechanism within the columns, although mineralization and vegetative uptake also were important. Contaminant volatilization was negligible and leaching of the contaminant was minor after some initial washout. Enrichment of the naphthalene degrader community ($p<0.05$) in the columns was measured using biodegradation batch experiments. The vegetated columns experienced enhanced enrichment compared to the unplanted columns ($p<0.05$). This research suggests that vegetation not only provides enhanced aesthetic appeal to bioretention cells, but also measurable pollution control benefits.

Introduction

Surprisingly, little is known about the ultimate fate of stormwater petroleum hydrocarbons in bioretention areas. Petroleum hydrocarbons are often collected by stormwater runoff from impervious surfaces such as streets and parking lots. A wide array of potential sources of petroleum hydrocarbon pollution exists in urban catchments, including motor vehicles, leaky storage tanks, parking lot and roadway runoff, automotive emissions, illicit dumping, spills, tire particles, and parking lot sealcoats (Davis et al. 2001; Davis and McCuen 2005; Mahler et al. 2005; Watts et al. 2010). Coal tar-based pavement sealcoats are recognized as a source of carcinogenic polycyclic aromatic hydrocarbons (PAHs) to urban stormwater (Mahler et al. 2005; Watts et al. 2010; Yang et al. 2010). In some urban watersheds, pavement sealcoats account for the majority of PAH loading to streams (Mahler et al. 2005). Petroleum hydrocarbon concentrations in road runoff have been measured from 0.2 to 277 mg/L (Wu et al. 1998; James et al. 2010; Kim et al. 2007; Barraud et al. 1999). Thus, urban stormwater often contains petroleum hydrocarbons. Petroleum hydrocarbons, such as oil and grease or PAHs, are toxic to aquatic life and may be carcinogenic to humans (Fent 2003; Mastrangelo et al. 1996).

One best management practice for stormwater management that has rapidly gained popularity throughout the United States is bioretention, including raingardens. To date, few studies have explicitly considered the fate of petroleum hydrocarbons in bioretention. Based upon the current literature, infiltration-based best management practices may be effective in removing petroleum hydrocarbons from stormwater (Davis et al. 2009; Weiss et al. 2008; DiBlasi et al. 2009; Hong et al. 2006; Hsieh and Davis 2005). Nevertheless, there is still a lack of knowledge as to the ultimate fate of petroleum hydrocarbons *within* the bioretention cell. Furthermore, concerns have been expressed that raingardens could accumulate pollutants or pollute underlying groundwater resources (Davis et al. 2009; Weiss et al. 2008; Pitt et al. 1996). Thus, it is important to determine if petroleum hydrocarbons are accumulating in bioretention soils and to understand the ultimate fate.

In this research, laboratory-scale experiments were performed to determine the fate of petroleum hydrocarbons in bioretention cells. Furthermore, the influence of vegetation on pollutant removal in general and biodegradation (i.e., mineralization) in particular was investigated. The goal of the work was to determine whether bioretention cells provide a sustainable treatment option for petroleum hydrocarbon-contaminated stormwater.

Methods

Three laboratory bioretention cells were assembled in sealed glass columns (Figure 1). Bioretention soil media ("Water Quality Mix A," MPCA 2008) composed of a 4:2:1 volume ratio of sieved construction sand, leaf compost, and topsoil was homogenized and packed loosely into the columns. Each column was operated under a different vegetation regime (unplanted, grass, clover). Vegetation was established using grow lights and then ^{14}C-naphthalene dissolved in synthetic stormwater (Hsieh and Davis 2005) was spiked into the columns. The column setup with ^{14}C tracer allowed for measurement of hydrocarbon fates. Leachate was collected from the reservoir at the bottom of each column. Volatilized naphthalene was captured in activated carbon traps fitted to Teflon tubing connected to a vacuum pump. Biodegradation was quantified by capturing mineralized $^{14}CO_2$ in fine bubble diffusers containing 2 M NaOH.

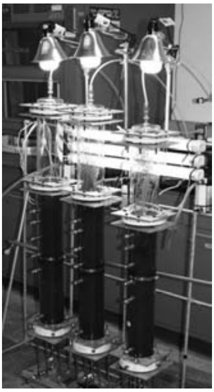

Figure 5. Laboratory bioretention columns (photo: LeFevre).

At the terminus of the experiment, the columns were disassembled. Vegetation tissue samples were analyzed for ^{14}C uptake using a biological oxidizer. Soil samples were taken every 7 cm of depth, and naphthalene and bacterial DNA were extracted. Naphthalene was measured using gas chromatography with flame ionization detection (GC-FID) and all ^{14}C measurements were made using liquid scintillation counting. DNA was analyzed to quantify for two biodegradation functional genes (naphthalene dioxygenase and phenol monooxygenase) and 16S rRNA genes (a measure of total bacteria) using real time quantitative polymerase chain reaction (qPCR).

Soil samples from the columns and the original bioretention soil media were used to inoculate nephelometric flasks in separate biodegradation batch experiments. These batch experiments provided mineralization rates, time to reach maximum mineralization, and total mineralization capacity All statistical analyses were performed using Stata 10.1.

Results

The bioretention columns successfully captured or degraded approximately 90% of the naphthalene influx for the vegetated columns, and approximately 80% for the unplanted control column. Naphthalene leaching was higher for the unplanted column than the two planted columns. Adsorption to soil was the single largest removal mechanism (>50%), although biodegradation and plant uptake were also significant. Volatilization of naphthalene was minimal (<1%). Comparing the two types of test vegetation, the ^{14}C sequestration in the grass was approximately five times greater than in the clover column. The total vegetative biomass of the grass was approximately twice that of the clover, but the concentration of ^{14}C residual was also significantly higher than in the clover tissue. Plant species appears to alter hydrocarbon fate in the bioretention cell.

The biodegradation capacity of the bioretention soil media used to pack the columns was compared to the soils from the columns at the end of the experiment (Figure 2). Although the original bioretention media was capable of biodegradation, the soils from the columns following pollutant exposure experienced statistically significant ($p<0.05$) reductions in the time required to reach maximum mineralization rate (the inflection point, henceforth referred to as "lag time"). This change indicates that the microbial community was enriched for contaminant degraders (Figure 2, Figure 3). The concentration of naphthalene dioxygenase genes in the bioretention soils also were significantly greater at the end of the experiment ($p<0.05$), supporting this finding.

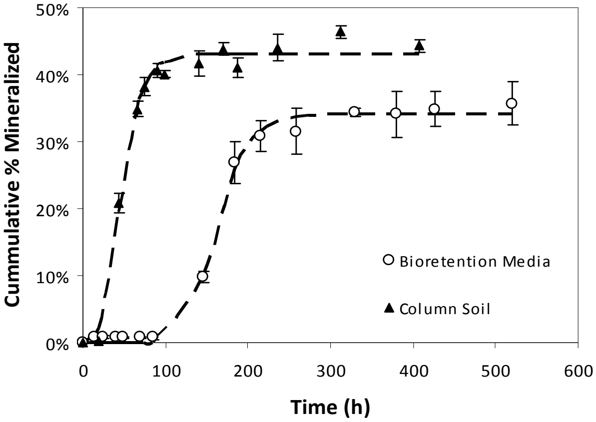

Figure 6. Comparison of mineralization profile of bioretention media and soil collected from one of the columns following the experiment. Points are mean± std. dev. of triplicate experiments.

The soils from the vegetated columns experienced a biodegradation lag time significantly less ($p<0.05$) than the unplanted column (Figure 3). Thus, the presence of vegetation appears to further stimulate the hydrocarbon degrading bacterial populations in bioretention soils.

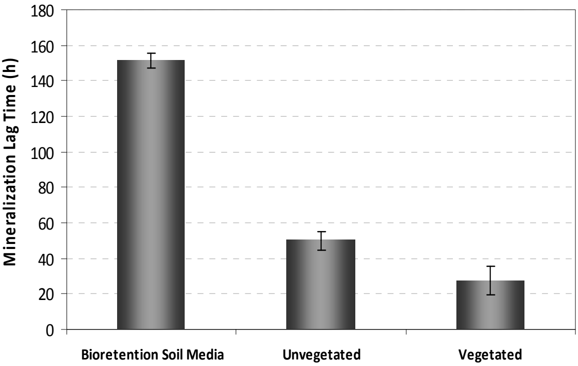

Figure 7. Comparison between the time to reach the maximum mineralization rate (lag time) between the original bioretention soil media, the un-vegetated column soils, and the vegetated column soils. Error bars indicate the 95% confidence interval.

Conclusions

Bioretention is an innovative approach to managing excess stormwater volumes and ameliorating the spread of many pollutants present in runoff. The results of this study indicate that bioretention will provide sustainable petroleum hydrocarbon removal at most sites. Vegetation is an often overlooked design parameter in bioretention, and our results indicate that plants may have measurable pollution control benefits in addition to their aesthetic appeal.

Acknowledgements

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Nutrient Retention Performance of Advanced Bioretention Systems Results from Three Years of Mesocosm Studies

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Abstract

Current bioretention designs are not very effective at nutrient retention for a variety of reasons. Negatively charged organic amendments compete for the few phosphorus (P) binding sites available in the sand matrix. The rapid rate of flow through the systems does not permit enough time for effective nitrogen (N) retention to occur. To improve bioretention designs for nutrient retention, it is necessary to understand the processes involved in nutrient transformations. Given this understanding, it is then possible to develop approaches that improve nutrient retentions.

Our mesocosm studies have shown that advances in bioretention system design substantially improve retention of N and P from runoff. Using advanced media, our research over three years has confirmed our initial findings on P retention trends. After accumulating 190 $g\text{-}m^{-2}$ P (the equivalent of nearly five decades of stormwater runoff), the advanced media had a median TP discharge concentration of 0.077 mg/l. The median Ortho-phosphate discharge concentration was 0.015 mg/l.

N retention by the outlet regulated treatment was 66% in even quite large (~6 month ARI) events, and 62% for oxides of N. The corresponding free discharge treatment was significantly less effective, at 27% and 19% retention respectively. A year later, total N retention in small storm events exceeded 70%, while nitrate retention exceeded 90%. These results confirm how advanced media combined with outlet controls substantially raise the bar for treating runoff nutrients. This is become ever more important with the adoption of strict numeric criteria in TMDLs in affected waterbodies throughout the US.

Introduction

Table 1 presents a generalized summary of bioretention performance for a variety of stressors. Numerous studies (as cited in Davis et al. 2009) document that bioretention performs well for total suspended solids (TSS) and associated particulate stressors, as well as metals and hydrocarbons. This is because bioretention is very effective at filtering solids, while the negatively charged organic amendments have a very high affinity for positively charged metals. Biological activity also effectively removes biological oxygen demand (BOD) and hydrocarbons.

However, many properties of typical bioretention systems also impede effective nutrient retention. Negatively charged dissolved P and N are actively repelled by the negative binding sites that dominate typical bioretention media. Furthermore, particulate nitrogen has many components that break down and are eventually transformed into negatively charged dissolved forms. As a result, retention of these forms of N and P is much less effective.

Table 1: Typical range of retention performance of bioretention systems expressed in terms of concentration as opposed to mass load reduction.

Runoff Stressor	Typical Inflow (mg/l)	Range of Reduction
Total Suspended Solids (TSS)	15-350	90-99%
Biological Oxygen Demand (BOD)	1.50-22.0	80-90%
Total Copper	0.01-0.28	60-90%
Total Zinc	0.03-0.35	85-95%
Oil and Grease	0.40-20.0	95-99%
Particulate Phosphorus	0.10-2.20	95-99%
Dissolved Phosphorus	0.05-1.50	***10-30%***
Dissolved Nitrogen	0.10-3.70	***-40-40%***
Particulate Nitrogen	0.50-3.50	***25-50%***

As P is often the limiting nutrient for freshwater impoundments such as lakes and reservoirs, excess P increases eutrophication by stimulating plankton growth. On the other hand, as N is often the limiting nutrient for estuarine waters, excess nitrogen causes eutrophication in these ecosystems, although P can also be implicated (Correll, 1999). N is the second most common element in living cells and P is a fundamental component of cellular metabolism. N is the fundamental element in all amino acids that make up proteins, and is also a basic component of DNA. N and P are typically found at a N:P ratio of approximately 16:1 in plankton.

To better understand how these nutrients can be removed more effectively, it is necessary to understand the various different forms of N and P, and how they respond to environmental conditions. In this manner, it is then possible to develop methods and approaches that can improve nutrient retention.

Phosphorus

While concentrations of P in urban runoff may be relatively low compared to agricultural ecosystems, urban runoff concentrations still far exceed that would stimulate eutrophication in lakes and reservoirs. Given the sheer volume of urban runoff, the resultant mass loads of excess P thus cause substantial impairment of freshwater environments. Excepting novel information, references have been omitted in the following discussion for brevity

Forms and Transformations of Phosphorus. Total phosphorus (TP) comprises both particulate (PP) and soluble phosphorus (SP). TP is predominantly PP comprising orthophosphate (PO_4-P) that has been adsorbed onto clay fractions containing iron and aluminum oxides and/or precipitated with calcium carbonates. PO_4-P is a reactive dissolved form that makes up most of SP. Whether adsorbed or in solution, PO_4-P is considered inorganic P. Other dissolved forms of P include polyphosphate and inositol. Together with PO4-P, these filterable species of P are called soluble reactive P (SRP).

Organic phosphorus (OP) can comprise labile (readily metabolized) particulate forms such as algal cells that rapidly decompose. It also has soluble forms such as inositol that can be tightly bound to soil particles. Outside of a small fraction of dissolved OP, PO_4-P in solution is the only form taken up by algae. Even though OP as inositol may be represent a proportion of TP, most of this is not bioavailable due to its tight binding to soils, and so it is typically included as part of PP. Dissolved OP (DOP) is generally a small proportion of total P in runoff.

Sorption. The great majority of the resulting complexes are irreversibly bound at environmental concentrations. As a result, PO_4-P adsorbed onto iron and aluminum complexes are released only if the concentration is below a low equilibrium threshold, so most of this pool of P is unavailable to algae. As a result, only a small portion (between 5-20%) of PP is considered bioavailable. The proportion depends upon forms of P adsorbed, sediment sorption properties, and water column concentration relative to the amount of PO_4-P adsorbed to suspended sediments. Under anoxic conditions often found in eutrophic sediments, PO_4-P can also be released from ferrous precipitates of PO_4-P.

Algal and Plant Uptake. Due to algal uptake, high levels of PO_4-P are rarely observed in stream and lake sampling results, as any PO_4-P entering solution is rapidly taken up by algae in the water column. As the solution concentration declines, more PO_4-P is released from the PP pool until there is equilibrium is reached between algal uptake and PP dissolution. Thus governed by algal and sediment kinetics, PO_4-P levels in even eutrophic water bodies are often quite low, in the range of 0.005 to 0.030 $mg\text{-}l^{-1}$.

Plant uptake of P can be as high as 16.5 $g\text{-}m^{-2}\text{-}y^{-1}$ when subjected to P concentrations an order of magnitude higher than runoff (Greenway and Lucas 2010). Under more typical bioretention conditions similar to fertilized crops, P uptake is in the range of 0.9-2.2 g-.m^{-2}-y^{-1} (Flaten et al. 2003). Given that bioretention systems are subjected to annual loads in the range of 5 g-m^{-2}-y^{-1} (Hsieh et al. 2007; Lucas and Greenway 2008), plant uptake thus represents at most a fraction of the P applied.

On the other hand, we have documented that the presence of plants is instrumental in improving P retention. However, while the presence of plants substantially improved P retention, plant uptake represented less than 20% of the increase in P retention compared to unplanted (barren) treatments (Lucas and Greenway 2008). Using media formulated for P retention, the proportion was even less, ranging from 13 to 15% (Greenway and Lucas, unpublished data). Therefore, even though plants are essential for best retention performance, plant uptake comprises only a small proportion of P retained. As such, uptake per se does not represent a major component of P retention in bioretention systems.

Immobilization. The fact that the presence of plants has an effect of that far exceeds actual uptake suggests that other biological processes are involved. We hypothesize that microbial immobilization may be the basis for this paradoxical observation. Microbial activity dominates soil processes; in temperate grassland soil biomass ranges from 1,000-2,000 kg-ha^{-1} while fungal biomass can range from 2,000-5,000 kg-ha^{-1}, so the resultant microbial activity is responsible for 80-90% of all soil processes, and over 90% of the soil energy budget (Nannipieri et al. 2004).

Furthermore, microbial uptake (immobilization) processes can be very rapid. Even in soils with a very high P sorption capacity, immobilization is even more rapid than sorption, taking up the majority of P applied. The amount sequestered in one pulse can be as much as half the estimated microbial biomass P (Olander and Vitousek 2004a; b).

Since microbial processing requires inputs of energy (priming) in the form of carbohydrates produced by plants (Paterson 2003), there would be much less soil microbial biomass without plants, and so immobilization activity would be reduced. Indeed, Henderson (2009) found that microbial immobilization rates in media from the mesocosms of Lucas and Greenway (2008) were higher in the planted mesocosms compared to unplanted mesocosms.

This process of rapid immobilization provides a mechanism that seems to explain the much better performance provided by planted systems. By providing the energy to drive microbial immobilization processes, plants provide the setting where enhanced retention of intermittent P pulses can occur. Figure 1 presents a schematic of how the processes of dissolved P retention can be portrayed. The thickness of the various arrows represents the relative dominance of the various pathways.

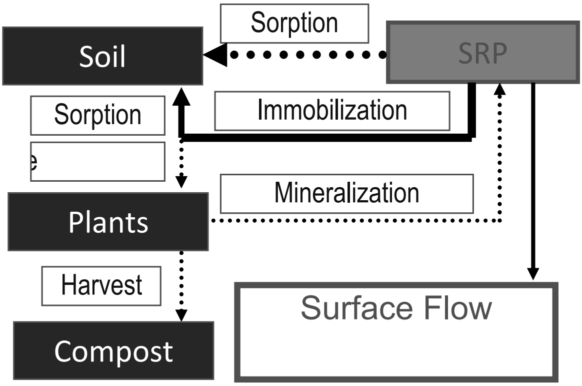


Figure 1: Processes involved in dissolved phosphorus retention

Phosphorus Retention Processes in Bioretention Systems. As indicated above, the PP that typically dominates total P loads is essentially irreversibly bound to soil particles which can be easily filtered. The SRP immobilization response is hypothesized to dominate initial SRP retention, with the ultimate sink being the media, so geochemical process of adsorption is the primary mechanism by which SRP is permanently retained in bioretention treatments. Therefore, the media must include as much amorphous aluminum as possible for effective SRP retention, and the systems have to be planted (Lucas and Greenway 2008; 2011a). On the other hand, if the media is already saturated with P, the equilibrium concentration is so high that a substantial amount of PO_4-P is exported from the soil profile (Hunt et al. 2006). This happens because the relatively few positive sites in the sand matrix are rapidly saturated with P, as shown in the unvegetated column studies of Erickson et al. (2007) and Hsieh et al. (2007). Meanwhile, the negatively charged organic compost actually competes with PO_4-P for these sites. Furthermore, the labile (easily broken down) organic components can leach appreciable quantities of SP (Bratieres et al. 2008).

Even though retention of SP is often reported as effective (eg., Davis et al. 2006, Henderson et al. 2007), the vast majority of studies reporting these findings examine newly installed systems in which the sand matrix is not yet saturated, so they do not represent the true performance of bioretention over decades. As the only study of simulated long term retention of typical bioretention systems, our previous work (Lucas and Greenway 2008) showed that effective P retention will not persist for even a decade, and even less if no plants are present.

Several other salient points are indicated in Figure 1. Note that plants have various stages of senescence, the process of shedding biomass during dormancy. Trees drop their leaves, and grasses die back to the ground. This process releases OP back into the environment. In the case of OP, most of the resultant SRP is likely to be retained within the media via the immobilization/sorption pathway. One way to reduce any potential losses is to harvest the plant material and compost it so it can be recycled.

Nitrogen

As in the case of P, N loads in urban runoff also exceed loads that would stimulate eutrophication. The resultant mass loads of excess N thus pose substantial detriment to estuarine environments. Again, references have been omitted in the following discussion for brevity except for novel information.

Forms and Transformations of Nitrogen. Total nitrogen (TN) comprises oxidized forms of inorganic N such as nitrate (NO_3^-) and nitrite (NO_2^-). Since NO_2^- readily transforms into NO_3^- and is thus much less prevalent, many researchers use the term nitrogen oxides (NO_x) to represent both of these species of N. The more reduced form of inorganic N is ammonium (NH_4^+). Organic nitrogen (ON) is the most reduced (combined into larger molecules such as proteins, amino acids and DNA). It can be a substantial proportion of total N. The reduced forms of NH_4^+ and ON are often called total Kjeldahl N (TKN).

As the most complex form, ON includes both refractory and labile forms. The more refractory forms of ON are large molecular weight compounds immobilized within hemi-cellulose and lignin complexes found in decayed plant material. This form of ON generally behaves as particulate material. However, most ON in runoff is more labile, meaning that it can readily be hydrolyzed into amino acids which are ammonified into NH_4^+. As such, ON represents a substantial pool of potential N which can eventually be taken up by algae directly. Note that algae cells themselves are comprised of entirely labile ON that is readily hydrolyzed/ammonified back into NH_4^+ upon their death.

NH_4^+ formed from the breakdown of labile ON is also soluble, but since it readily adsorbs onto soil particles due to its positive charge, it generally does not travel through soils at appreciable quantities. Instead, NH_4^+ is rapidly nitrified (oxidized) to NO_x since this reaction requires no external energy. Both NO_x and NH_4^+ are considered inorganic N, and are readily taken up by algae, microbes and higher plants.

As the end product of oxidation reactions, NO_x is often the predominate form of dissolved N found in runoff in many settings. NO_x is very mobile, so it moves with surface runoff during storms, as well as in subsurface flow, thence entering streams as baseflow. Once in the groundwater, NO_x is conservative, that is, it will not be bound by soil particles so it can easily be transported into estuaries. NO_x is readily taken up by algae, so high levels will have considerable trophic impacts, particularly in haline and saline waters. Figure 2(a) displays the various interactions of these forms of N under oxic conditions.

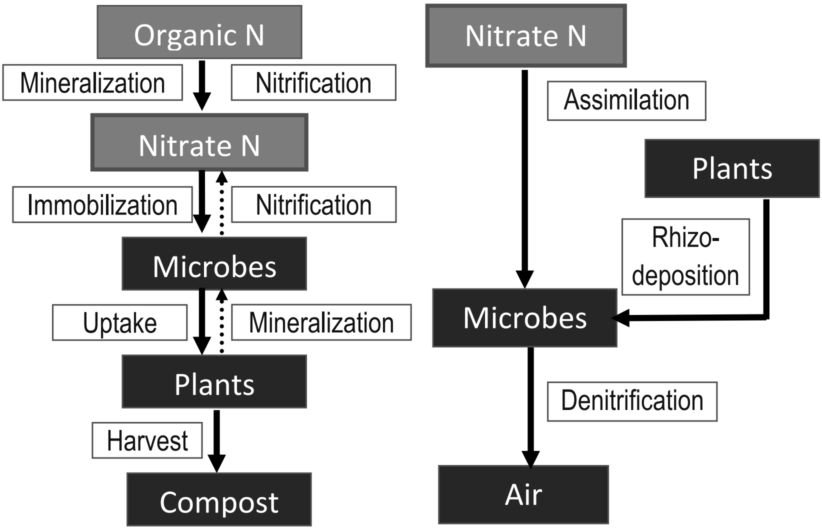
NO_x can also be denitrified to dinitrogen gas (N_2) in anoxic settings where oxygen is absent. Unlike the preceding dissimilatory reactions, denitrification requires an energy source, which is typically provided by higher plants. Since it is less efficient than oxidation, it proceeds in anoxic settings. Depending upon temperature, denitrification is a relatively slow reaction requiring many hours or even days to complete. Figure 2(b) displays the interactions of these forms of N under anoxic conditions. Note that anaerobic is not a technically proper term for anoxic settings, as NOx itself provides reduction process that is mediated by a molecule including oxygen.

Immobilization. A key aspect of these reactions is their time dependency. Microbial immobilization occurs more rapidly than plant uptake (Hodge et al. 2000), so it is the initial process by which N is retained in soil (Recous et al. 1992; Kaye et al, 2001). NH_4^+ can be immobilized five times faster than NO_3^- (Accoe et al, 2005). Upon turnover at cell death, N is either mineralized back into NH4+ by extracellular enzymes secreted by other microbes, or incorporated into soil organic nitrogen (SON) as long term immobilization (Schimel and Bennett, 2004).

In soils high in organic matter (OM), immobilization rates can approach 1.0 g-m^{-2}-d^{-1} (Barrett and Burke 2000). Inselbacher et al. (2010) measured up to 0.6 g-m^{-2}-d^{-1} over the first four hours. Since OM content accelerates microbial respiration, immobilization rates increase in the presence of plant residues (Barrett and Burke 2000). Given bioretention event loads of a similar magnitude, these rates suggest that several hours of retention time could be adequate for immobilization of IN found in runoff.

Mineralization and Nitrification. Following microbial immobilization of IN and ON, mineralization, ammonification and nitrification by microbes turns over NH_4^+ and NO_3^- into the rhizosphere for subsequent plant uptake (Recous et al, 1992). Initial immobilization/synthesis is rapidly recycled to ensuing mineralization and nitrification (Accoe et al, 2005). In N enriched settings, nitrification represents the dominant pathway for NH_4^+ transformation (Schimel and Bennett, 2004). The high nitrification rates observed in enriched crop soils by Inselbacher et al. (2010) suggest that nitrification is likely to be a substantial transformation in bioretention systems, as inferred by Davis et al. (2006) and Lucas and Greenway (2008; 2011c).

Denitrification. Given adequate organic carbon energy sources when anoxic conditions are present, denitrification will also transform NO_3^-. In favorable conditions, hourly observations suggest that denitrification is a first order reaction approaching completion in 10-12 hours (Whitmore and Hamilton, 2005). When established, plant rhizodeposition provides adequate amounts of biomass energy for denitrification even at high N loading rates (Kadlec and Wallace, 2009).



(a) Oxic N transformations **(b) Anoxic N transformations**

Figure 2: (a) Processes involved in oxic N transformations between and organic inorganic forms. (b) Processes involved in anoxic N denitrification.

Plant Uptake. Plant uptake in the aboveground shoots and stems and belowground roots and rhizome is the final step in a sequestration process initially mediated by immobilization. Annual uptake in treatment wetlands varies from 15 g-m^{-2}-y^{-1} to as high as 84 g-m^{-2}-y^{-1} (Kadlec and Wallace 2009). Uptake in the subtropical bioretention mesocosms used in this experiment ranged from 48 to 77 g-m^{-2}-y^{-1} (Greenway and Lucas 2010). N uptake is much more effective in certain plants than others (Read et al. 2008; 2009; Greenway and Lucas 2010), and such increased uptake has been correlated with better N retention (Bratieres et al. 2008; Read et al. 2009; Greenway and Lucas 2010).

The greatest above ground biomass N uptake occurs in an annual cycle, beginning in spring, peaking past midsummer, and declining in the autumn. Accumulated N is then released during senescence over the winter (Kadlec and Wallace 2009). If uptake is to be considered a viable process for N retention, it is therefore necessary to harvest above ground biomass at least annually (Kadlec and Wallace 2009).

Nitrogen Retention Processes in Bioretention Systems. This background provides the framework for interpreting the type of N transformations that can be expected with N processes. Due to N transformations, individual N atoms “spiral” through wetlands as they cycle between N forms while moving from different compartments before being eventually discharged. Given the inertia of this cycling, effluent parameters are inevitably affected by the legacy of preceding N inflows (Kadlec et al, 2005). N cycling time is thus many multiples of hydraulic residence time in wetlands. Similar but accelerated cycling is likely to occur in bioretention systems. A salient fact about these transformations is that they all eventually oxidize all other forms of N to NO_x, which is very mobile, and thus difficult to retain.

Many N retention processes will be diminished without plants. Not only will plant uptake be entirely eliminated, but NO_3^- immobilization and denitrification will also be inhibited, as these endergonic processes require more energy than available in runoff. Meanwhile, immobilization of ON and NH_4^+ requires much less energy, so reduced N can be retained. As an exergonic reaction releasing energy, nitrification can then readily transform reduced N into NO_3^-. With no inter-event uptake and minimal denitrification, NO_3^- retention is negligible. As a result, NO_3^- is often exported by unplanted (barren) systems (Henderson et al, 2007, Bratieres et al. 2008; Lucas and Greenway 2008; 2011c).

Observations of immobilization, nitrification, and denitrification rates suggest that substantial bioretention N loads can be intercepted and transformed within a period as short as three to four hours in planted systems. As such, it is to be expected that better N retention would be correlated with slow infiltration/application rates (Davis et al. 2006; Lucas and Greenway 2008; Passeport et al. 2009), and/or low hydraulic loading rates relative to media pore volume (Zinger et al. 2007; Read et al. 2008; Bratieres et al. 2008).

Low infiltration rates permit more residence time during events, while low hydraulic loading rates permit more runoff to be retained within the system until discharged at the next event. As an example, Lucas and Greenway (2008) observed cumulative TN retention was highest in the loam treatment with infiltration rates of 1 $cm\text{-}h^{-1}$, while TN retention in sand treatment restricted to 5 $cm\text{-}h^{-1}$ was half as effective. However, the very slow loam treatment could not treat nearly as much volume, resulting in more flows being bypassed as the systems overflowed.

Advanced Bioretention System

The preceding discussion suggests that improved media can be combined with outlet controls to improve nutrient retention. Media can be amended with materials with a high P sorption capacity to improve P retention. The advanced bioretention system (ABS) patented by the principal author (Lucas 2010; 2011) contains high amounts of alum from water treatment residuals (WTRs). Adding WTR amendments to media greatly improves P retention (Lucas and Greenway 2011a).

Increasing hydraulic retention time also increases N retention. The outlet used in the ABS provides a novel approach to resolve the conflicting goals of restricting flows to extend retention time for N retention, while minimizing bypass flows. This is accomplished by a dual stage outlet (Lucas 2010; 2011). The lower outlet is elevated above the stone layer so as to provide a saturated zone and regulated to provide a flow rate of approximately 8 cm-h^{-1} when the media begins to pond.

It is supplemented by an upper outlet that flows when ponding occurs, with its flow rate determined by media saturated hydraulic conductivity (K_{sat}) and relative head. Due to high K_{sat} in the media, this arrangement allows for substantial flows to pass through the media. With such an outlet, the plug flow retention through rapidly infiltrating media time increases to 150 minutes compared to the free discharge retention time less than 20 minutes (Lucas and Greenway, 2011b). This resulted in greatly improved N retention compared to free discharge bioretention systems typically used (Lucas and Greenway, 2011c). Detailed discussion of the Methods and Results are included in the preceding papers and patents, and will not be included here in the interests of brevity.

Figure 3 describes the fundamental elements of the ABS. In settings where N is a concern and the underlying soils are highly permeable (> 10 cm-h^{-1}), the system is lined so that flows can be regulated by the outlet. Otherwise, flows pass too rapidly for effective N retention and simply divert surface N runoff into groundwater, which is counter to N TMDLs such as in the Chesapeake Bay. As such, observations of N load reductions in surface runoff cited in Davis et al. (2009) actually represent increased N loads, since the concentrations of NO_x increased in these studies. As such, it is erroneous to suggest that infiltrated NOx do not represent an accelerated load into groundwater, as all of the infiltrated NO_x is eventually discharged.

The liner creates a permanently saturated zone with its elevation set by the lower outlet. An advantage of this arrangement is that the system can be placed within the water table to the extent that the lower outlet has free discharge. The liner can be eliminated if soils infiltration rates are slow enough that there is adequate time for N transformations. In this case, the saturated zone will eventually drain, which will improve both recharge and effective storage available for the next event. However, by retaining runoff in the media instead of being discharged through the underdrain, the lower outlet will also increase the amount infiltrated compared to the uncontrolled discharge used in conventional bioretention systems.

Improving upon the system described in Lucas and Greenway (2011b; c) the depth of stone and the saturated zone is increased to at least 50 cm so as to provide more volume for storage between events. This will further improve N retention by storing more runoff between events while also increasing the effective retention time.

The other essential component of the ABS is the media. Blended with other refractory organic material, the advanced media has a very high K_{sat} ranging from 30 to 60 cm-h^{-1}. This high rate not only delays the onset of clogging, it also maintains higher rates of flow for a longer period of time (Le Coustumer et al. 2009). Using the adaptive management capabilities of the upper outlet, design performance can be maintained even when K_{sat} declines to 1/10th of the initial rate (Lucas and Greenway

2011b). Due to its WTR amendments, the media is capable of very high P retention, even when subjected to over 3 decades of urban runoff (Lucas and Greenway 2011a).

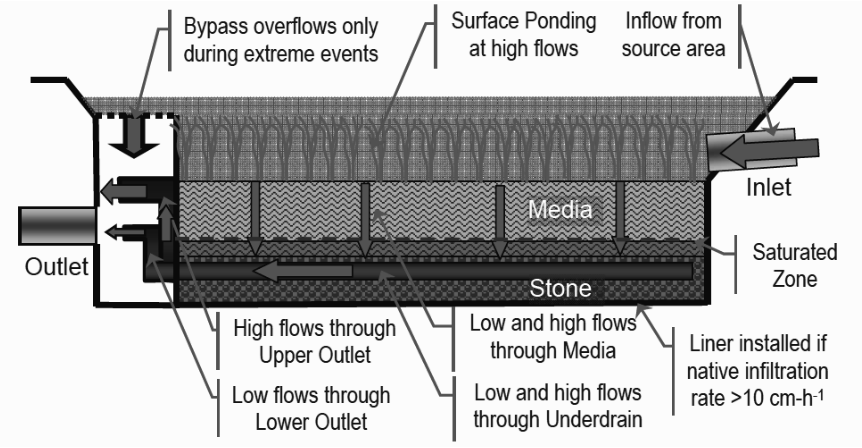


Figure 3: Fundamental elements of the Advanced Bioretention System patented by the principal author

Advanced Bioretention System Performance

The initial N and P retention performance of the ABS presented in Lucas and Greenway (2011a; 2011c) showed that TDP retention from stormwater after over 30 years of urban runoff was 93%, with 99% retention of PO_4-P. We are not aware of any other accelerated load studies outside of our study on sandy media (Lucas and Greenway 2008) and the barren columns subjected to P concentrations an order of magnitude higher than ours of Hsieh et al. (2007). These studies showed minimal or no retention after the equivalent of 5 to 10 years of loads, in distinct contrast to our findings with advanced media (Lucas and Greenway 2011a).

Our results from quite large events (approximately 6 month recurrence interval for Brisbane Australia) showed TN retention of 66%, with NO_x retention of 62%. The corresponding retention in the typical bioretention systems was 27% and 19% respectively. This documented the benefits of the outlet of the ABS in increasing N retention. When subjected to a smaller dose representative of a more typical event, TN retention increased to as high as 78%, while NOx retention was as high as 94%. The ABS was able to provide a significant increase in N retention compared to the corresponding free discharge treatment.

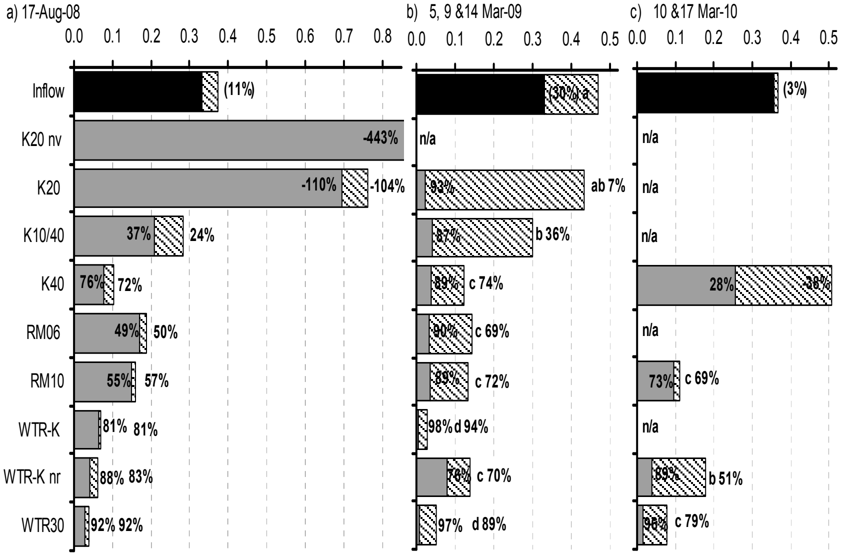


Figure 4: Total dissolved phosphorus (hatched) and PO4-P (solid) inflow and outflow, (mg-l-1). a) All treatments, 17 August 2008 (80 weeks for initial 6 treatments, 50 weeks for last three treatments). b) All vegetated treatments, three events 5-14 March, 2009 (110 weeks for initial treatments, 80 weeks for last three treatments). c) Most effective treatments, 10-17 March 2010 (163 weeks for first treatment, 133 weeks for last three treatments). Percent of orthophosphate retention listed on left, percent of DP retention on right. Statistical differences between treatments indicated with different letters. Combinations including letters that are the same as other treatments are not significantly different.

This section presents selected results from another year of observations. Figure 4 presents a comparison of P retention responses to stormwater applications over a period of 17 months from August 2008 to March 2010. Note the remarkable trend of performance improving between the August 2008 and March 2009 observations. This would not be expected from sorption theory. The fact that the proportion of TP was dominated by OP at this time suggests a response involving microbial immobilization, as hypothesized in the Introduction.

Even after another year of loading, P retention in the WTR treatment remained at 79%, with 96% PO_4-P retention. This was observed after nearly 200 g-m^{-2} applied, or the equivalent of nearly 5 decades of urban runoff loads. Clearly, the WTRs used in the ABS have enough capacity to effectively retain P from runoff for the entire anticipated life of a bioretention system.

As noted previously, N retention from stormwater was remarkably effective at a lower dose typical to most events once the systems had matured enough. In this regard, it is instructive to examine the N retention response to elevated N concentrations at this time. Given that N transformations are microbially mediated, it would be expected that retention of N from the low loads would be highest, as there is less N to be transformed in the short time available.

Figure 5 presents the results from the effluent loading runs during the winter of 2009 when plants were dormant. This figure represents the flow-weighted concentrations from 22 different effluent loading events. Even at concentrations several times higher than urban runoff applied at very high rates, the retention of N was even higher than the stormwater runs of March 2009 presented in Lucas and Greenway (2011c). TN retention was as high as 73%, while NO_x retention was no better than 50%.

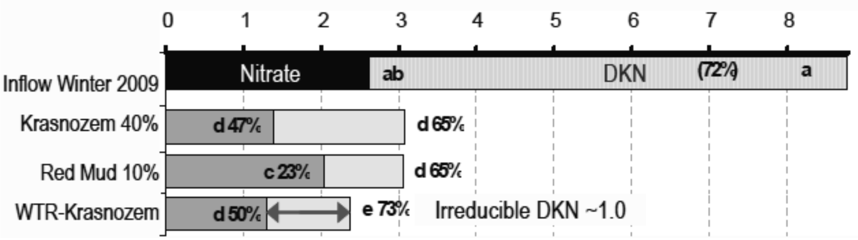


Figure 5: Total dissolved nitrogen (hatched) and NO_x (solid) inflow and outflow, (mg-1^{-1}). Most effective treatments (after 110 weeks for initial treatments, after 80 weeks for WTR-K treatment). Percent of NO_x retention listed on left, percent of TDN retention on right. Statistical differences between treatments indicated with letters.

The NO_x retention of 50% was less effective than from stormwater. As noted in Figure 5, TN was dominated by dissolved TKN (DKN) which was nitrified, so the amount of NO_x transformed was actually much higher. This is demonstrated by the TN retention observations as high as 73%. This retention represents over 6 mg-l^{-1} retained in each event. Clearly, the systems were capable of very high TN retention rates, even if NO_x retention was less in absolute terms. Reflecting the higher loads, the irreducible DKN concentration was in the range of 1.0 mg-l^{-1}. These results suggest that ABS could be very effective in agricultural ecosystems as well.

Conclusions

The background and results presented in this paper demonstrate that it is possible to effectively retain nutrients contained in runoff if the underlying processes are effectively manipulated to retain nutrients under the stochastic nature of urban runoff flows. By providing the proper media amendments and controlling flows with a regulated outlet configuration, it is possible to retain the vast majority of P, and most of the N in runoff. The potential afforded by the ABS has the potential to substantially reduce nutrient loads in locations subjected to nutrient TMDLs.

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Bioretention Performance Findings from the International Stormwater BMP Database

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Introduction

The International Stormwater BMP Database (BMP Database) is a long-term project that began in 1994 through the vision of members active in the Urban Water Resources Research Council of the American Society of Civil Engineers (ASCE) and leadership of the U.S. Environmental Protection Agency (EPA). Funded for many years by EPA, the project is now supported by a coalition of partners including the Water Environment Research Foundation, Federal Highway Administration, American Public Works Association, as well as ongoing support from ASCE's Environmental and Water Resources Institute. The project is a long-term, multi-faceted effort that includes guidance on BMP monitoring (Geosyntec and WWE 2009a), standardized database reporting information, and recommended performance analysis protocols.

The BMP Database contains performance data for over 510 BMP studies, including over 265,000 water quality records, along with precipitation and flow data. BMP categories in the Database include both traditional BMPs and Low Impact Development (LID) practices such as bioretention, permeable pavement, grass swales and buffers, green roofs, and site-scale LID studies. Data submitted by researchers from throughout the United States and several other countries are provided in a standardized format enabling comparison of the performance of BMPs with various design parameters, watershed settings, maintenance conditions, etc. The BMP Database project includes a master database that can be used for independent research, including individual BMP performance summaries and BMP category-level performance analysis, which are publically available for download at www.bmpdatabase.org.

As of July 2012, approximately 30 bioretention studies from Delaware, Massachusetts, North Carolina, New Hampshire, Oregon, Pennsylvania, Virginia, Washington and Wisconsin are included in the BMP Database. Fifteen studies are located in North Carolina, four studies are located in Wisconsin, three are located in New Hampshire, three are located in Virginia, and the remaining states each have one bioretention study. The studies include a variety of designs installed in differing watershed conditions. Approximately 80% of the designs are characterized as bioretention cells (non-linear, not associated with conveyance), with other design variations such as in-line bioretention areas, planter boxes and other configurations. Design information reported with bioretention studies is relatively well developed and includes information on facilities with traditional underdrains, "internal water storage zone" underdrain configurations, as well as sites without underdrains. For example, approximately two-thirds of the installations have underdrains, about half incorporate some form of pretreatment (e.g., sedimentation forebay, buffer strip, etc.), and seven are designed to incorporate an "internal water storage zone." Many of the bioretention BMPs have been monitored in pairs to assess design variations such as deep vs. shallow depth, clay vs. sandy soil, turf vs. native grasses, and other factors. Performance data for these studies can be obtained from the International Stormwater BMP Database website (www.bmpdatabase.org) in several different formats, including: 1) statistical summaries for individual BMPs, which can be downloaded from the on-line search tool; 2) a new technical performance summary series, which contains BMP-category level performance; or 3) the master database, which can be used for independent analysis. Additionally, researchers can go directly to the original study using the links identified in the references portion of this conference paper.

The purpose of this conference paper is to provide highlights of bioretention performance analyses from a broad technical performance summary series completed during 2010-2011 and updated in 2012, which focused on the topics of fecal indicator bacteria, nutrients, solids, metals, and volume reduction.[1] These five topical technical summaries provide an overview of the regulatory context, unit treatment process information, data summaries, conclusions, recommendations and statistical summaries for various BMP categories. Statistical appendices accompanying these topical summaries include descriptive statistics and a series of graphical representations of the data such as box plots, probability plots, and scatter plots. **Be aware that this conference paper provides only selected excerpts from these papers and is intended to provide a general sense of the information that is available with regard to bioretention; the underlying technical summaries should be downloaded from www.bmpdatabase.org for more complete information**. Findings related to bacteria are not provided in this conference paper due to the limited number of bioretention studies with bacteria data available at the time that the bacteria analysis was completed. Selected findings from the remaining topics are provided below, focusing first on water quality constituents, then discussing volume reduction. Although pollutant effluent concentrations and volume reduction are discussed separately, it is important to keep in mind that pollutant load reduction for most bioretention facilities has a significant volume-related component.

Total Suspended Solids

Excessive sediment can adversely impact aquatic life and fisheries, source

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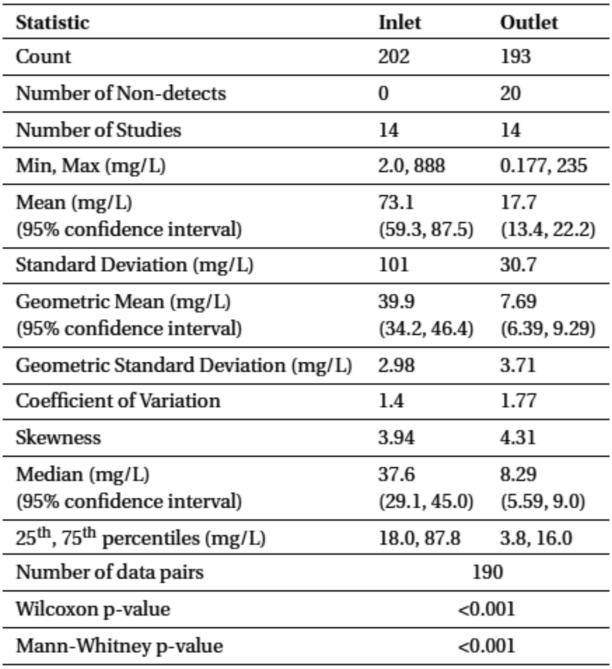
[1] Statistical summaries are updated periodically. The data summaries referenced in this paper are based on data available as of July 2012.

waters for drinking water supplies, and recreational uses. Fine particulates also often carry other pollutants such as heavy metals, PCBs, and other pollutants. Therefore, removal of suspended sediment from runoff can also reduce sediment-bound pollutants. Table 1 below provides an example of information contained in the statistical summary for total suspended solids (TSS) at bioretention BMPs as part of the BMP Database Pollutant Category Summary for Solids (Geosyntec and WWE 2011, with statistical appendices updated in 2012). In addition to basic descriptive statistics, hypothesis test results are provided for paired and unpaired inflow-outflow data, using the Wilcoxon signed-rank test and Mann-Whitney rank-sum tests, respectively, as shown in Table 1. Accompanying Table 1, Figure 1 provides a box plot illustrating the bioretention-TSS data set graphically, along with a probability plot that provides a quick method of identifying the probability that an individual sample would be less than or equal to a particular value.

Table 1: Summary of Total Suspended Solids at Bioretention BMPs
(From Geosyntec and WWE 2012a, “Solids Statistical Appendix”)



Statistic	Inlet	Outlet
Count	202	193
Number of Non-detects	0	20
Number of Studies	14	14
Min, Max (mg/L)	2.0, 888	0.177, 235
Mean (mg/L) (95% confidence interval)	73.1 (59.3, 87.5)	17.7 (13.4, 22.2)
Standard Deviation (mg/L)	101	30.7
Geometric Mean (mg/L) (95% confidence interval)	39.9 (34.2, 46.4)	7.69 (6.39, 9.29)
Geometric Standard Deviation (mg/L)	2.98	3.71
Coefficient of Variation	1.4	1.77
Skewness	3.94	4.31
Median (mg/L) (95% confidence interval)	37.6 (29.1, 45.0)	8.29 (5.59, 9.0)
25th, 75th percentiles (mg/L)	18.0, 87.8	3.8, 16.0
Number of data pairs	190	
Wilcoxon p-value	<0.001	
Mann-Whitney p-value	<0.001	

Based on hypothesis test results and comparison of the 95% confidence intervals for the median inflow (38 mg/L) and outflow (8 mg/L) values in Figure 2, it is clear that bioretention provides excellent reduction of TSS. Additional analyses conducted as part of the Solids Technical Summary enable comparison of bioretention performance for TSS relative to other BMP types, as shown in Figure 2. For example, the effluent concentrations achieved by bioretention studies show that bioretention is one of the better-performing BMP categories for reducing TSS in urban runoff, although many BMP types appear to effectively reduce TSS.

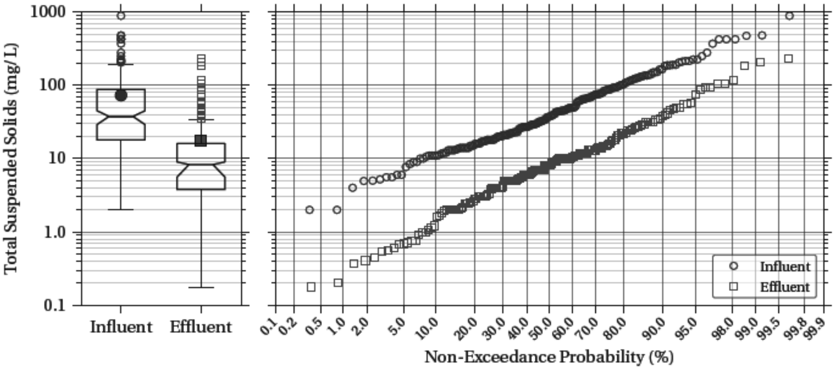


Figure 1: Box and Probability Plots of Total Suspended Solids at Bioretention BMPs
(From Geosyntec and WWE 2012a, "Solids Statistical Appendix")

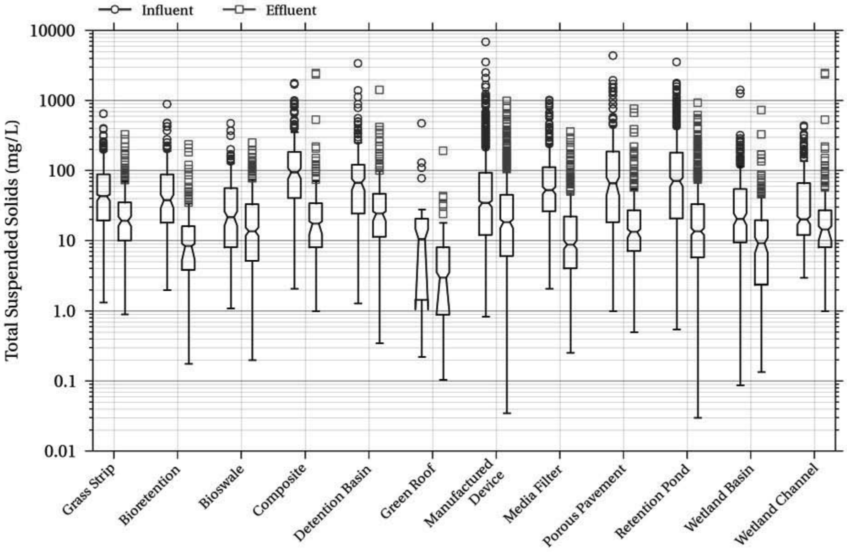


Figure 2: Box Plots of Influent/Effluent TSS Concentrations by BMP Type
(From Pollutant Category Summary Statistical Addendum: TSS, Bacteria, Nutrients, and Metals, Geosyntec and WWE 2012a)

Metals

Metals are among the most common stormwater pollutants, with key sources including automobile-related activities and exposure of building materials to rain. The bioretention data set had adequate numbers of samples to conduct analysis for total copper, iron, and zinc, with detailed statistical summaries provided in the "Pollutant Category Summary Statistical Addendum: TSS, Bacteria, Nutrients, and Metals" (WWE and Geosyntec 2012). Although large percentages of non-detects affected the data analysis for several BMP-metal combinations, the bioretention data set for these three metals was relatively unaffected by non-detects. Figures 3, 4 and 5 provide box plots and probability plots of total copper, iron and zinc at bioretention BMPs. Similar to the information provided in Table 1 for TSS, hypothesis test results for the bioretention data set showed statistically significant reductions for total copper and zinc. Effluent concentrations for total iron were significantly higher than influent concentrations for this data set. It is expected that native soils and engineered media mixes may have high iron content, which may be mobilized under reducing conditions, affecting iron concentrations in bioretention effluent.

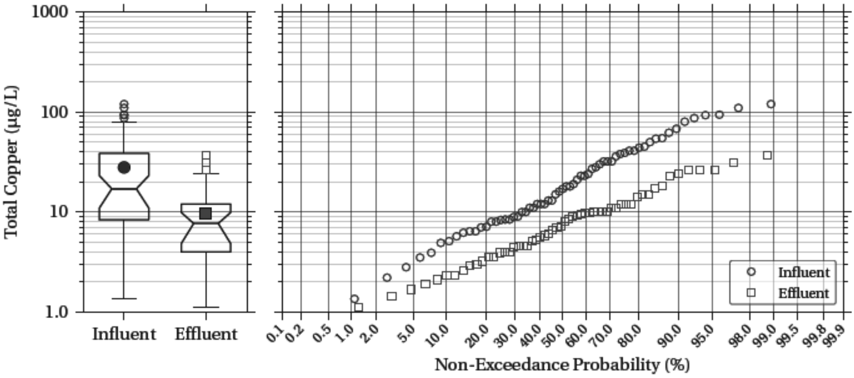


Figure 3: Box and Probability Plots of Total Copper at Bioretention BMPs
(From WWE and Geosyntec 2012a, "Metals Statistical Appendix")

Nutrients

As of 2010, over 14,000 water bodies across the country were listed as impaired for nutrients, organic enrichment, algal growth, and/or ammonia. As examples of nutrient analyses performance results for bioretention, Figures 6 and 7 provide box plots for total phosphorus and total nitrogen, alongside results for other BMP categories. For complete analysis results see the "BMP Database Pollutant Technical Summary for Nutrients" (Geosyntec and WWE 2010, with statistical appendices updated in 2012).

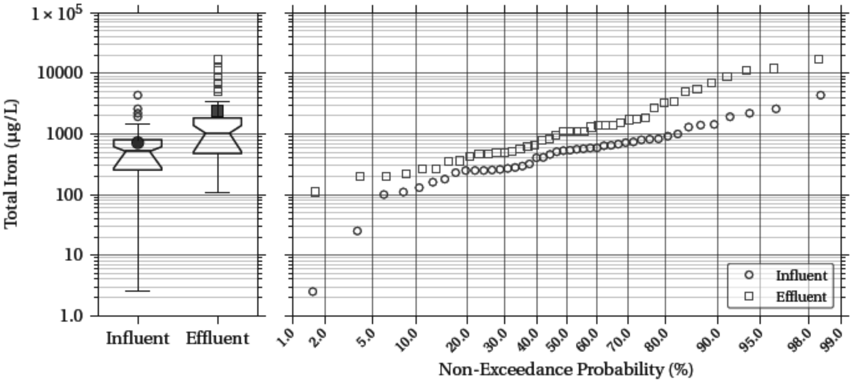


Figure 4: Box and Probability Plots of Total Iron at Bioretention BMPs
(From WWE and Geosyntec 2012a, "Metals Statistical Appendix")

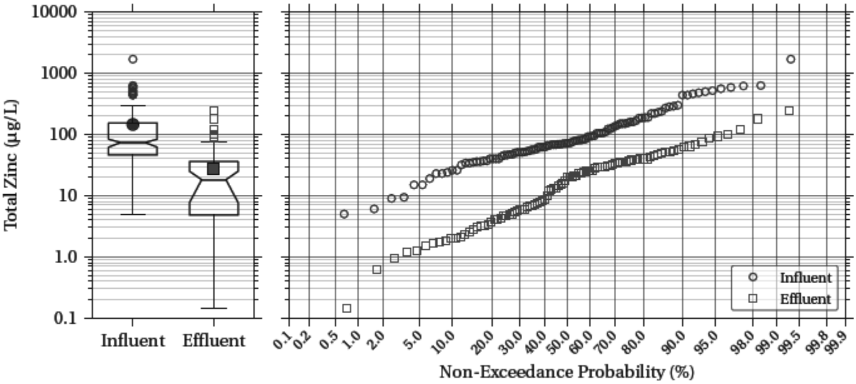


Figure 5: Box and Probability Plots of Zinc at Bioretention BMPs
(From WWE and Geosyntec 2012a, "Metals Statistical Appendix")

The studies currently included in the analysis data set for bioretention did not show a significant reduction in total phosphorus concentrations; however, bioretention cells have low effluent concentrations comparable to BMPs that show statistically significant differences between influent and effluent concentrations. Leaching of phosphorus from soils/planting media and resuspension of captured particulate phosphorus may be a cause of phosphorus increases observed in vegetated BMPs such as bioretention, swales, and filter strips. In the case of some of the BMPs included in this particular analysis, original research by the data provider documents that phosphorus-rich infiltration media resulted in increases in phosphorus in the effluent concentrations. Specifically, Hunt et al. (2006) found that bioretention cells using a fill soil media with a lower phosphorus index (P-index) provided much better phosphorus removal than those which used a high P-index fill media. This resulted in the recommendation that fill media characteristics are a critical design parameter related to total phosphorus removal.

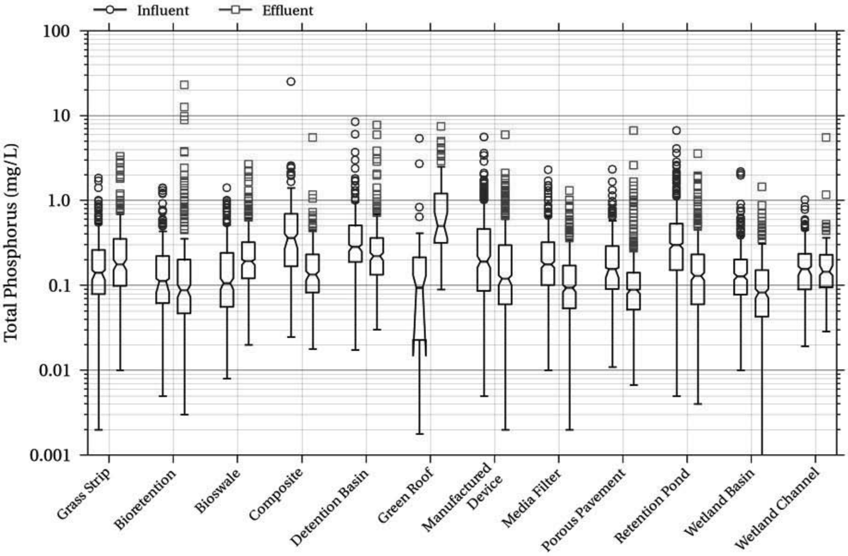


Figure 6: Box Plots of Influent/Effluent Total Phosphorus Concentrations by BMP Type

(From Pollutant Category Summary Statistical Addendum: TSS, Bacteria, Nutrients, and Metals, Geosyntec and WWE 2012a)

Figure 7 graphically summarizes total nitrogen concentration data for various BMP types, including bioretention. (See the Nutrient Technical Summary for supporting information related to numbers of studies, storm events, etc.) Statistically significant reductions in total nitrogen concentrations were identified for bioretention. BMP categories with permanent pools (e.g., retention ponds, wetland-pond composite systems) also demonstrated reductions in total nitrogen concentrations. Additionally, it is important to keep in mind that reduction in nutrient loads by bioretention is often achieved by reducing the volume of stormwater discharged.

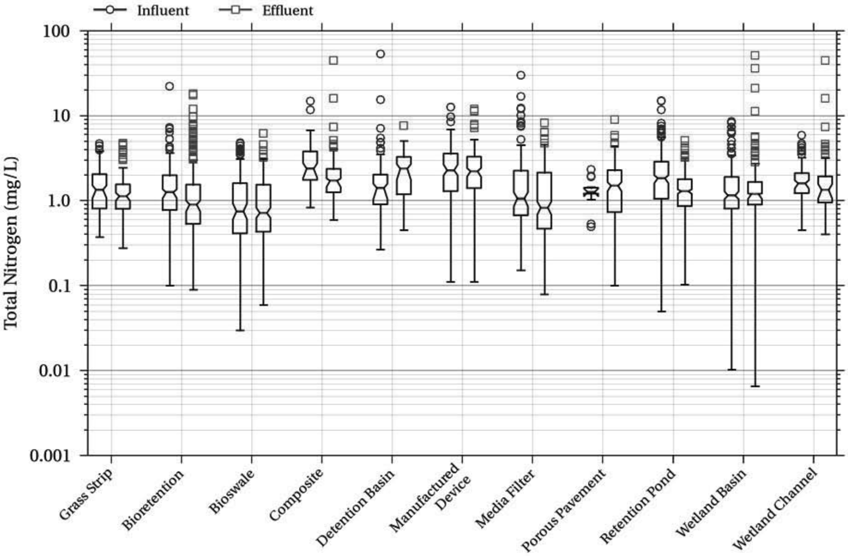


Figure 7: Box Plots of Influent/Effluent Total Nitrogen Concentrations by BMP Type
(From Pollutant Category Summary Statistical Addendum: TSS, Bacteria, Nutrients, and Metals, Geosyntec and WWE 2012a)

Volume Reduction

The hydrologic performance of stormwater BMPs is an important factor in the overall effectiveness of BMPs in reducing potential adverse impacts of urbanization on receiving waters. In addition to providing water quality data, the BMP Database also provides information related to the hydrologic performance of BMPs such as watershed characteristics, precipitation data, and flow data. Initial analysis of volume reduction at bioretention facilities focused on bioretention data sets with underdrains (Geosyntec and WWE 2010); however, growth in the bioretention data set enabled expanded analysis of bioretention without underdrains in 2012 (Geosyntec and WWE 2012b). A combination of metrics was applied to evaluate volume reduction, as described in “BMP Database Technical Summary for Volume Reduction” (Geosyntec and WWE 2010). Although use of a combination of multiple metrics is recommended, for purposes of this broad overview of volume reduction findings, Table 2 provides a summary of the relative volume reduction provided by various “normally dry” BMP categories in the BMP Database. Normally dry BMPs are those that are not designed to maintain a permanent pool of water. In this analysis, all storm events with paired inflow and outflow were summed within studies and relative volume reduction was calculated for each study. These study results were then pooled by BMP category (e.g., bioretention, detention basin) and summarized.

Table 2: Study-weighted Relative Percent Volume Reductions Observed for Normally Dry BMP Categories

(From Geosyntec and WWE 2010b, "Volume Reduction Technical Summary," August 2010 Data Set; with Updated Analysis for Bioretention Data Set July 2012 from Geosyntec and WWE 2012b)

BMP Category	# of Studies	25th Percentile	Median	75th Percentile	Average
Biofilter – Grass Strips	16	18%	34%	54%	38%
Biofilter – Grass Swales	13	35%	42%	65%	48%
Bioretention (with underdrains)	14	33%	52%	73%	56%
Bioretention (without underdrains)	6	85%	99%	100%	89%
Detention Basins – Surface, Grass Lined	11	26%	33%	43%	33%

NOTES

Relative percent volume reduction for each study = 100 x [(Study Total Inflow Volume - Study Total Outflow Volume)/(Study Total Inflow Volume)]

Summary does not reflect performance categorized according to storm size (bin). This is an important limitation of this summary, since large storms that may result in bypass or overflow conditions may not be represented in the limited period of record typically associated with BMP monitoring.

As shown in Table 2, the BMP categories considered in this analysis suggest significant surface runoff volume reduction. Variability in study performance is relatively wide. These numeric estimates may be useful at a planning level with consideration of the reliability of input datasets and the potential role of design criteria and site conditions on volume reduction performance. These results may be useful in estimating the range of performance that could be expected within a BMP category over a range of conditions and design standards; however, these generalized estimates are not appropriate to predict the volume reduction performance of a specific BMP designed to specific design criteria for a specific set of site conditions.

Additional analyses presented in the Volume Reduction Technical Summary (2010) and a more detailed analysis of bioretention without underdrains in 2012 show excellent volume reduction. Additionally, bioretention with underdrains also exhibits relatively high volume reductions, especially for smaller storm events. Bioretention appears especially effective in preventing discharge during small events; the majority of inflow events less than 1 watershed-cm in volume result in very low or zero outflow (Note: Discharge via underdrains is considered to be surface discharge in these studies.)

Conclusion

The bioretention data set in the International Stormwater BMP Database is a growing resource useful for developing a better understanding of bioretention performance with regard to both volume reduction, effluent concentrations and pollutant load reductions. The bioretention data set will be of increasing value to the technical community as more studies are added to better represent bioretention performance under various watershed and climate conditions. Data available to date show that properly designed, installed and maintained bioretention facilities can be an effective tool in reducing runoff volumes and pollutants loads.

References

Hunt W. F., Jarrett, A. R., Smith, J. T., and Sharkey, L. J. 2006. "Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina." *Journal of Irrigation and Drainage Engineering*, 132(6)600-608.

International Stormwater BMP Database Project Website (www.bmpdatabase.org). Work products prepared by Wright Water Engineers and Geosyntec Consultants under support from U.S. Environmental Protection Agency, Water Environment Research Foundation, Federal Highway Administration, Environmental and Water Resources Institute of the American Society of Civil Engineers. WERF Project No. 03-SW-1COe1. Referenced work products include:

- *International Stormwater BMP Database Pollutant Category Summary Statistical Addendum: TSS, Bacteria, Nutrients, and Metals (*Geosyntec and WWE 2012a*)*
- *International Stormwater BMP Database Addendum 1 to Volume Reduction* (January 2011); *Expanded Analysis of Volume Reduction in Bioretention BMPs* (Geosyntec and Wright Water Engineers, 2012b)
- *International Stormwater BMP Database Pollutant Summary Category: Fecal Indicator Bacteria* (WWE and Geosyntec 2010)
- *International Stormwater BMP Database Pollutant Summary Category: Nutrients* (Geosyntec and WWE 2010a)
- *International Stormwater BMP Database Pollutant Summary Category: Volume Reduction* (Geosyntec and WWE 2010b)
- *International Stormwater BMP Database Pollutant Summary Category: Solids* (TSS, TDS and Turbidity) (Geosyntec and WWE 2011)
- *International Stormwater BMP Database Pollutant Summary Category: Metals* (WWE and Geosyntec 2011)
- *Urban Stormwater BMP Performance Monitoring* (Geosyntec and WWE 2009)

Links to Websites for More Information on Bioretention Studies in the BMP Database

Delaware Department of Transportation (http://www.deldot.gov/stormwater/bmp.shtml)
North Carolina State University Department of Biological and Agricultural Engineering Stormwater Engineering Group (http://www.bae.ncsu.edu/stormwater/)
Bureau of Environmental Services, City of Portland, OR (http://www.portlandonline.com/bes/index.cfm?c=34598)
Massachusetts Department of Recreation and Conservation (http://www.mass.gov/dcr/watersupply/ipswichriver/demo1-lid.htm)
University of New Hampshire Stormwater Center (http://www.unh.edu/unhsc/)
Villanova Urban Stormwater Partnership (http://www3.villanova.edu/vusp/)
Virginia Department of Transportation (http://virginiadot.org/vtrc/main/online_reports/pdf/01-r7.pdf
United States Geological Survey (USGS) - Wisconsin Water Science Center (http://wi.water.usgs.gov/index.html)
Washington State Department of Transportation (http://www.wsdot.wa.gov

Ballard Roadside Raingardens, Phase 1 – Lessons Learned

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Abstract

This paper covers the experience and lessons learned from the Ballard Roadside Raingarden, Phase 1 Project. This project involved installing bioretention facilities along eight blocks of City right-of-way for combined sewer overflow reduction goals in 2010. This paper details the design and construction experience and where Seattle Public Utilities (SPU) made missteps that resulted in the removal of 40% and retrofit of 50% of the constructed raingardens.

Background

A $1.4 million American Reinvestment and Recovery Act (ARRA) loan funded this project to build bioretention cells or “roadside raingardens” along eight blocks in the Ballard neighborhood, located in NPDES Basin 152. In 2010, 63 combined sewer overflows (CSOs) were observed in this basin, exceeding the regulatory standard of one overflow per outfall per year and discharging approximately 40 million gallons of combined sewage into Salmon Bay.

Seattle Public Utilities (SPU) has successfully constructed numerous bioretention systems in creek watersheds that control flows to urban creeks, called natural drainage systems (NDS), and mitigate 232 acres of drainage area to urban creeks. In contrast to NDS projects, BRR1 is SPU’s first project constructing bioretention cells in the right-of-way (ROW) to reduce the volume of stormwater entering the combined sewer system, thereby reducing the control volume. It is also the first significant retrofit in a neighborhood that already had a curb and gutter drainage system, as compared to unimproved (gravel) roadway shoulders. Since SPU had only conceptual designs for a curb and gutter road configuration but had not worked with Seattle Transportation Department or the community for their implementation this project was identified as a pilot project.

This project began as a conceptual design in the spring of 2009 to pilot roadside raingardens for CSO control, which included developing and piloting several different design configuration templates with the community. SPU was told that it was likely to receive funds at the beginning of July 2009, and was formally awarded the ARRA loan on August 17, 2009. ARRA rules required that the 90 percent plans and specifications and Engineering Report be submitted to Ecology for approval by September 17, 2009, and that the project be under a construction contract by February 16, 2010. Although the project met the required ARRA deadlines, the start of construction was intentionally delayed until June 2010 to avoid working in the wet season and to reduce the number of constructed, unplanted cells during the summer since they could not be planted until the fall. Unfortunately, for a variety of reasons (e.g. early rains, insufficiently protected raingarden cells which flooded and had to be pumped out, and design changes that required more information and slowed down the work), the construction period was longer than originally estimated and construction was not completed until the end of December 2010.

Consistent with the nature of pilot engineering projects, the BRR1 project encountered challenges. Two major challenges included lower performance than anticipated (that is, drainage in a majority of the bioretention cells was inadequate or too slow due to the presence of low infiltrating soils) and poor public involvement and communication. The public outreach problem made the performance problem more difficult to address. Both of these challenges provided an opportunity for SPU to learn valuable lessons to be applied to future projects.

Design Process

Project Management. This project did not prepare a Project Management Plan (PMP), which outlines the project scope, budget, roles and responsibilities, performance requirements, schedule, and communication plan and is now required for all SPU projects. As a result, the roles and responsibilities were not clearly defined, in addition to the overall project goals and expectations.

Basis of Design. The bioretention cells in BRR1 were designed to infiltrate approximately 95 percent of the stormwater volume from the area draining to each cell, which is roughly equivalent to the one-year event. The one-year event is the control target because State and Federal law require the City to reduce the overflows from each CSO basin down to no more than one overflow per site per year. The bioretention cells were designed to meet this goal based on the pre-sized tables that SPU developed for the City of Seattle Stormwater Manual, Volume 3 (Stormwater Manual). The original design was anticipated to reduce the 4.07 million gallon control volume in NPDES Basin 152 by 59,000 gallons, or 1%.

Geotechnical. The geotechnical evaluation included 19 modified pilot infiltration tests (PIT) that were completed in early August 2009 throughout the larger project area, which included blocks that were not ultimately selected. Six soil borings and monitoring well installations were completed in late October 2009 as a result of community feedback suggesting the presence of a high groundwater table and their concerns about infiltrating where there is already a groundwater problem. Preliminary infiltration rates, determined from pilot infiltration tests (PITs) that measured saturated hydraulic conductivity, were presented to the team in early August 2009, with the draft and final geotechnical reports completed in early and late November 2009, respectively. These draft and final geotechnical reports were completed at essentially the same time as the final design.

Design. This project was intended to pilot raingardens in the ROW for CSO control and to develop design templates for application of raingardens for different street configurations and infiltration rates. The cell design followed the standard design requirements for side slopes, setbacks, and bottom slope provided in the Stormwater Manual. The templates were important for detailing how to fit the cells into the available area given the site constraints and traffic control requirements, such as distance from end of curb and whether the curb could be moved out into the roadway and for what distance. A critical element in developing these templates was ensuring sufficient bottom area, the flat area in the bottom of the cell, because it provides the surface area through which most of the infiltration occurs, which is the primary mechanism for meeting our design goal. On many blocks that had a relatively narrow (< 9.5 feet) planting strip, this proved challenging and led to the development of the curb extension design which moves the curb up to five feet into the roadway for a short distance (Figure B, next page) and allows for a larger bottom area.

Due to the tight timeline, this project skipped preliminary engineering and moved directly into 30 percent design. In addition, in an effort to keep soft costs down and pilot the implementation of template designs, no survey was completed and the exact location of the cells had to be field directed, meaning that because there were no survey points to identify the specific cell locations, the design engineer had to work with the contractor to identify in the field where each cell should begin and end. This approach was identified when SPU thought that the project would only involve working in the planting strip (Figure A) or adding curb extensions (Figure B) along a small portion of the block length. However, it was not revisited for the design involving full block curb shifts (Figure C), which moves the curb out along the entire block.

The final design included one block with raingardens only within the planting strip, four blocks with both planting strip and curb extension raingardens, and three blocks with full block curb shifts. The full block curb shifts were possible only on 28th Avenue NW due to the overly wide roadway width (up to 44 feet in some places).

Project streets were selected based on a number of factors including:

- Street slope < 5%
- Planting strip width > 9.5 feet and/or ROW width > 58 feet
- Lack of established trees or landscapes
- Frequency of driveways not restricting the available length in planting strip
- Native soil design infiltration rates > 0.25 inches per hour
- Located within an existing CSO Long Term Control Program (LTCP) flow monitoring basin and would already have data that was gathered for model

development in support of the LTCP but could also be used as post-construction data for BRR1

Figure A-Planting Strip Example

Figure B-Curb Extension Example

Figure C-Full Block Curb Shift Example

The design went from 30 percent conceptual design to 90 percent in about two months. This required making quick decisions with short review times. As a result, the results and recommendations from the geotechnical report were not thoroughly incorporated into design. Based on past NDS designs, this project applied short-term infiltration rates instead of the corrected rates; however, on past projects the uncorrected rates were greater than 0.5 inches per hour so if the recommended correction factor of 2 had been applied, the raingardens still met the minimum requirements, which was not the case for this project. And in some cases on this project even the short term rates were below the minimum design standard. In addition, because of the short timeline and the quick selection of project streets, the infiltration data were based on only one test per block, and in some cases interpolated based on upper and lower block data. The uncorrected test pit rates ranged from 0.2 in/hr to 5 in/hr. Currently, the City's Stormwater Manual requires at least two tests per project block, but at the time of the geotechnical evaluation for this project, the revised geotechnical requirements were still in draft format and were not applied.

Construction. Construction began at the end of June 2010. Based on an estimate of 107 working days by the SPU Construction Management group, it was anticipated that construction would reach substantial completion by the end of September. This would allow the cells to be planted in October and allow the vegetation to establish during the winter months. However, the lack of survey data also resulted in project redesigns and delays. For example, the selected contractor felt that shaping of the cells, weir placement, and cell slopes required more refined elevation data than was provided. In addition, bad weather caused construction delays. The contractor's erosion and sediment control plan relied on placing sandbags in the curb cuts, which proved to be completely insufficient as the winter storms hit. The cells flooded every time it rained, creating further delays in construction. Substantial completion actually occurred in late December 2010.

Finally, three critical steps did not occur during construction on BRR1 that occurred on previous NDS projects:

1. Review of project goals and objectives with construction management staff, including critical design elements
2. Geotechnical engineer evaluation of excavated cells to verify soils
3. Thorough and timely communication with community

Community Outreach. While the BRR1 pilot project was in the design stage, educational materials that explain the broader CSO program context were being developed to describe the overall CSO problem that SPU needs to solve and the appropriate tools (e.g., bioretention, permeable pavement, storage tank, weir retrofits). Because this material was not yet available, the BRR1 project team tried to cover this CSO program context information during the project community meetings. During the course of design, SPU held two community meetings in Ballard (July 29, 2009 and October 13, 2009). The first meeting introduced the problem, the proposed project, pictures of the finished result of similar projects, and the potential project streets. The second meeting again presented the problem and project, pictures, and the chosen project streets. A final pre-construction community meeting was held on May 12, 2010 to introduce the contractor and review the schedule for construction and anticipated impacts. These meetings were the primary outreach to the Ballard community. Attendance at the first meeting, when SPU introduced the problem and project, had the lowest attendance, only 24 residents, and there was no follow up with a more aggressive outreach at this point.

Although SPU did not provide adequate outreach to the specific project community, SPU did host a walking tour on November 6, 2010. This tour included BRR1 Roadside Raingardens, in addition to Residential Rainwise raingardens (private property), and a test green alley (permeable pavement). The feedback was mixed, but was generally positive and people were interested in what SPU was doing.

Performance Results

The winter of 2010 was a very wet winter with the cumulative rainfall depth for the period October 2010 through March 2011 being 7 inches (27%) above the Long Term Average for Seattle. As construction was nearing completion in November and December, a significant number of the cells were not draining properly or even at all. When construction was finally completed and an accurate assessment of the cells' performance was made, SPU determined that approximately 33% of the cells were not draining, 33% were draining too slowly, and 33% were working as designed. Field observations by SPU and our geotechnical consultant determined that the non-draining and slow draining cells were a result of poor soils and a perched or mounded groundwater condition, which can often occur over glacial till soils. It became obvious that the design had not fully taken into account or understood the implications of low infiltrating soils and insufficient information.

The Ballard community was unhappy about the drainage performance and resulting standing water. Community leaders were vocal in demanding that the cells either needed to be fixed or removed. Community frustration and opposition to the project was covered in the media by two community blogs, newspapers, radio, and television. On February 2, 2011 SPU hosted a community meeting to present the problem and ask for the community's help and patience in finding a workable solution. The community expressed varied opinions about the raingardens, with some residents willing to keep the raingardens if they could be retrofitted to work properly, but the majority just wanting them to be removed.

A Task Force was formed with twelve community members and five SPU staff, including SPU's Deputy Director, to discuss the problem and possible solutions. The community was primarily concerned about the following issues:

- Long-term (>24 hours) ponded water
    - Drowning hazard for young children and the elderly
    - Mosquito breeding
    - Aesthetics
    - Smell
- Cell design
    - Side slopes too steep
    - Depth of allowable ponding
    - Depth of cell
- The presence of object marker signage on the curb extensions (the size, 12" wide by 36" tall, and look)
- Lack of communication and community input
- Loss of parking spaces

Figure D illustrates some of the non-functioning cells and the community concerns, such as long-term ponded water, the large black and yellow striped object marker signs, the parking restrictions, cell depth, and general aesthetics.

The Task Force met formally five times during March and April of 2011, with a few smaller informal discussions during that period, and came to a compromise on the design and presence of the raingardens. Because of the wide spread community dissatisfaction with the project SPU's communication, and the significant number of raingardens that were not draining, SPU found itself in a bad position to negotiate and ended up having to remove or retrofit (fill in to remove any visible ponding) many of the performing raingardens in order to gain community acceptance.

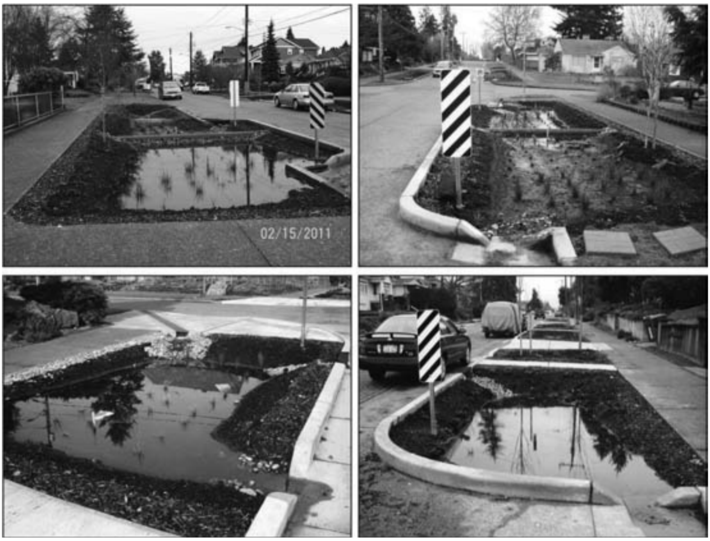

Figure D - Examples of Nonperforming Cells and Community Concerns

SPU Improvements

Based on the outcome of the Task Force meetings, the raingardens on 29th Ave NW and NW 77th St. will be completely removed, with the curb replaced back to its original location. Most of the raingardens on 31st Ave NW, along the east and west side of 28th Ave NW between NW 71st St and NW 72nd St, and along the east side of 28th Ave NW between NW 65th St and NW 67th St were retrofitted to be more shallow and remove any visible ponding, with several being completely removed.

The cells that were retrofitted to be more shallow have varying levels of infiltration due to the native soils conditions, but generally do not provide anything close to the intended performance and are classified as low performing or low infiltrating raingardens. Along the west side of 28th Ave NW, many of the raingardens are being redesigned as a detention system with an orifice-controlled underdrain. This design will capture the stormwater in the cell and temporarily store it in the bioretention soil (there is no surface ponding) while it waits to be slowly metered out to the combined sewer system by moving through the soil into the underdrain fitted with an orifice, which controls the rate of flow. A detention system helps with reducing CSOs by only allowing a little of the stormwater into the system when it is at capacity. Raingardens along 30st Ave NW work as designed and do not have any long term ponded water issues or community concerns, so no additional work or redesign is required.

The orifice controlled underdrain design along the west side of 28th Ave NW may become a prototype design for other areas of the city where the soils do not allow adequate infiltration, but the provided detention (or live storage within the soil) can be beneficial to the basin's overall CSO control requirements. The basic design includes a trench down the center of the cell with a slotted underdrain pipe surrounded by a filtering soil. An orifice at the downstream end of the underdrain pipe regulates the release rate of water into the combined sewer system. Several feet of bioretention soil are placed above the underdrain pipe to provide voids for water storage and good soil for plant growth. The appropriate depth and orifice size required to meet the basin's control volume requirements was determined by extensive SWMM5 modeling using the parameters of each block along 28th Ave NW.

The initial design was estimated to reduce the control volume in Basin 152 by 59,000 gallons. With the retrofits on all the streets in place, the new estimate is a 38,000 gallon control volume reduction, which represents 64 percent of the original goal.

Lessons Learned

Community Engagement.

- Get out into the community early, ideally a minimum of two years before project design meetings begin, and often. Introduce the problem you are trying to solve, before you present the solution.
- Don't rely on community meetings to educate the community about the project and to get their feedback, issues, and concerns. Develop several different strategies for communicating with the community and making sure they feel heard, such as one-on-one or small group meetings with residents, especially those that haven't attended the community meetings.
- Be clear with the community on:
    - How the raingardens work and why short-term ponding is important.
    - What the community could expect to see during early and late stages of construction.
    - What they can expect to see over the next few years as the raingardens mature, including ponding and changes in the vegetation look and size.
    - If there are going to be signs associated with the raingardens, be very clear with the community on what they will look like.
- Be clear on the "pilot" element of the project and how the community can help with the evaluation of its success.

- Understand the community “look” regarding street character and what’s important.

Planning.

- Develop a Project Management Plan (PMP) that outlines roles and responsibilities, schedule, budget, and risks and is approved by management.
- Hold regular team meetings to review project status and design.
- Clearly articulate the risks of accelerating a schedule to accept a grant or loan or meet some other deadline and communicate those risks to management and political staff. Be ready to proceed before accepting a grant or loan.
- If accepting a grant or loan, be sure to have clearly defined and allocated support from Grants and Contracts and Finance for filling out the forms and financial statements, the PM can’t do it on their own.
- Develop and communicate to the community the context of the problem and the toolkit of possible solutions before moving forward with implementing a project.
- When implementing a pilot project that sets the stage for future projects within a short timeframe, think through the goals and associated risks. For this project, given this well established community, it may have been better to pilot a single, lower impact design such as only constructing raingardens in the existing planting strip. Also consider the risks associated with consolidating many raingardens in one area for monitoring measurable performance.
- Be clear and get management support on the project policies, acceptable level of community impact (i.e., parking loss), and community acceptance threshold related to site selection criteria to avoid continual adjustments to the design and site locations during the design phase.

Geotechnical.

- Read the geotechnical report carefully and follow its recommendations, specifically using the corrected infiltration rates (not the short term rates) to determine site feasibility. Also, work more closely with the geotechnical engineers as project streets are selected and designed. Discuss whether, given the particular site conditions, more geotechnical data are required to increase the confidence in design.
- If the initial short term infiltration rate is less than 0.75 inches per hour for the sites that are applying that value, conduct in-depth subsurface evaluation per the 2009 City of Seattle Stormwater Manual, including wet season analysis. If the corrected infiltration rate is less than 0.25 inches per hour, anticipate that the geotechnical engineer will recommend a design that does not rely on infiltration. If the corrected infiltration rate is between 0.25 and 0.5 inches per hour, build a redundant system into the design, such as an underdrain.
- Follow the requirements for geotechnical evaluation in the 2009 Stormwater Manual, including ensuring adequate PITs along each project block, designing with corrected infiltration rates, testing for seasonal high groundwater level (not just the regional groundwater levels), and characterizing the infiltration receptor, which includes depth to groundwater and impermeable layers, seasonal variation in groundwater table, volumetric water holding capacity of the infiltration

receptor soils, horizontal hydraulic conductivity, and the impact of the infiltration rate and proposed added volume from the project on local groundwater mounding, flow direction, and water table. Although the Stormwater Manual was not finalized at the time of the geotechnical evaluation for this project, if the requirements in the Stormwater Manual had been completed, it is likely that the project would have performed as anticipated because raingardens would only have been located in areas with soils that are appropriate for infiltration.
- When conducting PITs, consider conducting them during the winter, especially in glacial till soils, and consider the ratio of sidewall to bottom area during the test and try to limit horizontal flow.
- Integrate the geotechnical engineers in all phases of the project, including construction. Empower them to speak up if they think infiltration is unlikely or high risk.
- Walk the site during the late wet season with an eye toward things that might suggest seasonal high groundwater – seeps, wet pavement along cracks or seams when the surrounding pavement is dry, saturated planting strips.
- Ask and listen to the community for clues to areas that might be problematic and require more investigation.

Design.
- Always complete preliminary engineering.
- Include a formal geotechnical review during the 30% circulation.
- Include a backup design in your plans, such as an underdrain, especially when the design infiltration rate is less than 0.5 in/hr.
- If a detailed survey is not desired, complete a "light" survey that focuses on critical elevations for streets and sidewalks and other critical points.
- When doing more than just working in the existing planting strip or adding a curb extension (< 40 feet in length), survey should be performed.
- If anticipating including a number of "field directed" elements in the design, work closely with the construction management group to evaluate this option against the proposed contracting approach and discuss how to make it feasible.
- Allow for a constructability review by Construction Management prior to finalizing design to produce a buildable contract plan (e.g., the specified payment method for the bioretention soil became problematic).
- Provide the design for the flow control/bypass plan and erosion and sediment control plan; don't leave it to the contractor. Also make sure it is enforceable and allows for additional measures as necessary to achieve the desired level of protection.
- Deliberately decide when the facility will be "turned on" to accept runoff.
- Review the project design, how it functions, and the critical project components with Construction Management ahead of time. All bioretention systems will require some level of field design; therefore, it is critical for the design team to articulate the design intent, the rigid requirements, and where there is flexibility.
- Don't be cheap with the plants – weigh cost of planting bigger stock initially to get better initial look for community.
- Identify lay-down areas on plans; try to avoid staging in front of homes.

- Consider raingarden payment by lump sum; if estimated quantities must be used, survey necessary to identify pre-construction grades/elevations for measurement/payment.
- If shallow utilities cross cells – avoid, relocate, or place sidewalks in those locations.
- Concrete removal limits – cut as rectangle, don't show curvy/diagonal saw cut, make long, straight cuts.

Construction.

- Balance funding sources with the ability to course correct during construction and the documentation requirements.
- Involve the geotechnical engineers during construction to field verify that the excavated or exposed soils look as anticipated.
- Prior to construction, develop internal response strategy for dealing with soils with lower permeability than anticipated within cells.
- Only assign staff to these types of projects if they are comfortable with projects that are very community intensive and not completely rigid.
- Maintain an open dialogue between the Contractor, Construction Management, Project Manager, designer, and geotechnical engineer.
- Review flow control and erosion and sediment control requirements and expectations with Construction Management staff to ensure raingardens cell receive adequate protection from siltation during construction.
- Clarify role of Street Inspector.

Looking Forward

SPU originally imagined a much different outcome for the Ballard Roadside Raingarden project. SPU still believes strongly in the value of bioretention as one of the tools for reducing CSO volumes, in addition to providing flow control in creek basins, and expects to continue to construct roadside raingardens into the future for both purposes. The number of very successful bioretention projects that we have implemented over the last 12 years, emphasizes that bioretention is an effective technology for reducing flows when applied where the conditions are appropriate. This project has highlighted the need to outreach and engage the community early and often, not try to rush things, and to continue to go back and review the technical assumptions and data with the project team. As SPU moves forward we will take the lessons learned from BRR1 and have greater success in the future.

A Green Street Retrofit in a Chesapeake Bay Community Using Bioswales

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Abstract

The Selby Bay community in Edgewater Maryland in Anne Arundel County was evaluated for opportunities to apply Low Impact Development (LID) Stormwater Management practices and Environmental Site Design (ESD) techniques in an effort to reduce discharges and gain water quality improvements. The community has very narrow right of ways (40 feet), many existing utilities, flat slopes and a high water table. The methods described in this paper can be applied in many coastal Bay communities to improve drainage and water quality.

A detailed hydrologic and hydraulic analysis of the study area was conducted with an innovative twist. In accordance with the provisions of the Maryland Stormwater Management Manual (MDE 2009, 2000), the TR-55 model was used to calculate the flows using the Runoff Curve (CN) number method. However, the modified CN approach (McCuen, 1983) was used to model the benefits of providing storage through use of swales. In general, this method uses a reduced CN and an increased time of concentration (Tc) to account for the flow attenuation provided by the swales.

Ultimately, the use of bioswales in the upper portions of the drainage area provide the following benefits: water quality treatment through infiltration and filtration processes, detention storage on-site both in the swales and in the biosoils that will be installed or enhanced under the swales, increased time of concentration by lagging the initial rainfall, reduced runoff curve numbers reflecting the infiltration and on-site storage, and a reduction of the downstream peak discharges allowing the use of smaller less expensive pipe systems to convey the runoff.

Introduction

The Selby on the Bay Community is located at the intersection of Central Avenue (Rt. 214) and Selby Boulevard as shown in Figure 1. This is an older bay front community located in Southern Anne Arundel County (AACo.), Maryland. The topography ranges from a sea-level condition along Selby Bay to an elevation of approximately 70 feet at the Selby Ridge subdivision. Although some streets have roadside ditches, the majority of the community does not have an adequate storm drainage infrastructure. As a result of the combination of the low-lying areas, the proximity of the water table location at or near the surface, and the absence of an adequate storm drainage system, the residents of the community are experiencing frequent minor flooding conditions and have made the Department of Public works aware of this condition through a number of drainage complaints.

The recommendation was made to design for the 2-year storm event, which will alleviate the frequent minor flooding conditions and provide water quality benefits at a lower cost (compared to the 10-year design).

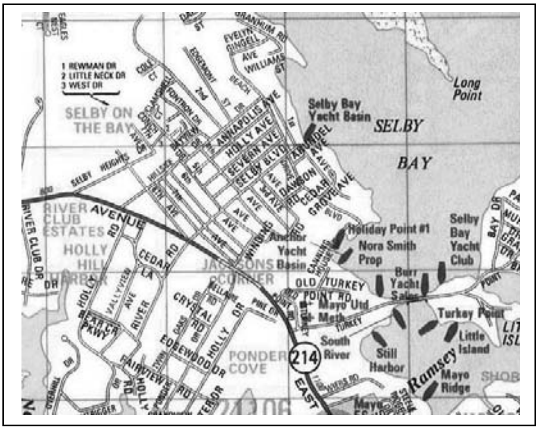

Figure 1. Vicinity Map of Selby on the Bay

Infiltration Tests

To locate LID opportunities, the first step was to determine where adequate infiltration capacity existed. Based upon the AACo. soil mapping most of the soils were in hydrologic soil group C which does not allow for infiltration under Maryland standards.

In situ infiltration tests were conducted and surprisingly positive results were obtained as shown in Table 1. The infiltration tests were conducted on June 12, 2009. The weather was dry, but there had been thunderstorm activity the day before on June 11, 2009.

Table 1. Infiltration Tests Summary

	Street	Infiltration Rate (in/hr)	DA
1	Fontron (W)	**7.5**	SA 22
2	Hillside (NE)	**0.75**	SA 23
3	Hillside (NW)	**8.5**	SA 22
4	Hillside (NW)	**1.75**	SA 21
5	4th & Annapolis (NE)	**4**	SA 37
6	Annapolis (NW)	**3**	SA 18
7	Annapolis (NE)	**3.5**	SA 37
8	4th (SW, between Annapolis & Holly)	**1**	SA 16
9	Holly (NW)	**4**	SA 15
10	Holly (NE)	**0**	SA 35
11	Severn (SW)	**1**	SA 10& 11
12	Severn (NE)	**1**	SA 31

Hydrology

Drainage sub areas were delineated based on topographic survey information and multiple site visits to verify actual site conditions on the ground. The longest hydrologic travel path begins in Subarea 23A (Fontron) and continues down to the Outfall. Most of the existing road infrastructure in this area is crowned in the middle thus distributing runoff to each side of the road.

The TR-55 program was used to determine the 2-year frequency storm discharge based on the soils, land use, and a cumulative drainage area and time of concentration (Tc) at each proposed inlet on the longest travel path. The Hydrologic Soil Groups (HSG) for the subareas were adjusted to represent the high infiltration rates as determined through the field tests.

Based on computed flows, a drainage system network was developed for the entire watershed to convey the 2-year design flows safely and efficiently to outfall without flooding. Every effort was made to avoid easements and maintain the horizontal and vertical clearance from existing utilities. The site being extremely flat has most of the area within a slope range of 0.5% to 2% with predominantly most of the roads at or about 0.5% slope. The water table is high due to proximity with the Bay. Relatively high water table and flat slopes in combination with a parallel existing pressure sewer system running along the main drainage corridor, posed great challenges to design a functional and workable system.

Bioswales

ESD *and LID* rely on integrating site design, natural hydrology, and smaller controls to capture and treat runoff (MDE 2010). The Selby Community already exhibits many ESD practices, specifically, narrow roadways, disconnected rooftops and grass swales. Under the new Maryland stormwater regulations, the Selby project qualified as neither 'new development' nor 'redevelopment' and therefore was not required to provide any ESD to the maximum extent practicable (MEP) by law. However, the County, Community, and Design Consultant agreed to provide ESD/LID via the proposed bioswales where possible to provide water quality benefits in keeping with the intent of the MD SWM act of 2007.

Location. Bioswales in the upper sub drainage areas (23A and 22) along Fontron provide storage and attenuation of flow, which increases the time of concentration (Tc) and reduces peak discharges (necessary to achieve discharge and Tc as modeled). In addition, bioswales offer water quality benefits by filtering pollutants from the road surfaces. Table 2. summarizes the bioswales' hydrologic location, dimensions, 2-year depth, and total volume. Figure 2 shows the proposed location of the bioswales along Fontron.

Swale location criteria included:

- Edge of swale at least 2' from edge of pavement
- Edge of swale within public right-of-way
- Top of swale at least 3' from proposed storm drain centerline
- Top of swale at or lower than surrounding grade
- Avoid conflicts with existing utilities, and driveway crossings

Table 2. Bioswale Summary Table

SA#	To Inlet	Length (ft)	Bottom Width (ft)	2-yr Depth (ft)	Width Top (ft)	Area Surface sf	Area subsurface (1.5*Wbase) with 40% void sf	Total Area sf	Total Volume cf
SA 23A	I-23A	95	7	0.16	10	1.4	4.2	5.6	528
SA 23	I-23	165	4	0.26	5	1.2	2.4	3.5	584
SA 22	I-22	178	4	0.37	5	1.6	2.1	3.7	656
SA 49	I-21	165	6	0.23	7	1.5	3.6	5.2	850
SA 36	I-36	75	3	0.19	4	0.7	1.9	2.6	197
SA 17	I-17	157	3	0.16	4	0.6	2.0	2.6	409
SA 35	I-35	160	3	0.28	4	1.0	1.7	2.7	431
SA 15	I-15	265	3	0.18	4	0.7	2.0	2.6	695
SA 12	I-12	122	4	0.11	4	0.4	2.1	2.6	311
SA 11	I-11	120	3	0.17	4	0.6	2.0	2.6	314
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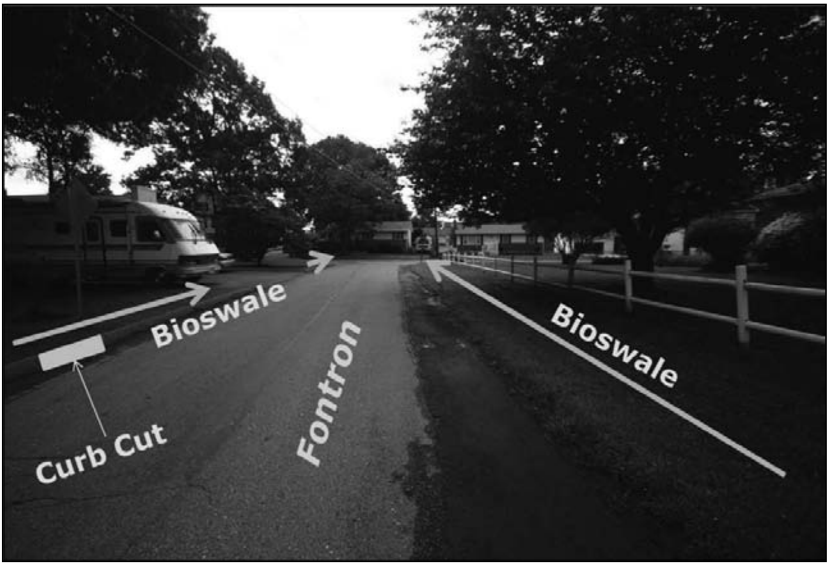


Figure 2. Proposed Bioswales Along Fontron (Upper Portion of the Drainage Area)

Bioswale Specifications

An innovative BMP, the in-situ bioswale was proposed. The in-situ bioswale is created by using a traditional grass swale but also includes deep disking of well-aged organic materials such as composted leaf mulch or pine fines into the existing soils to depth of 12 to 18 inches at 25% by volume (QAC, 2007). This eliminates the costs of excavating and disposal of existing soils and thus is a far more environmentally sensitive and sustainable approach which can reduce construction costs by 50% or more. Figure 3 shows a typical bioswale cross section.

The flows to each swale were calculated based on the individual subareas contributing to them using TR-55 or an assumed conservative flow (0.2 or 1 cfs depending on the subarea). Depth of water ranges from 1 to 4 inches for the 2-year discharges and from 2 to 8 inches for the 10 year discharges. Overflow elevations for swales were set at approximately the 2 year water surface elevation. Overflows enter inlets at either the grate elevation or invert of a throat opening or an overflow pipe connected to a perforated underdrain which is tied into the storm drain system. The swale dimensions were established to carry the 10 year storm event. Total depth of swales were set to either 0.5’ or 0.75’ with top widths ranging from 4 to 10 feet, side slows of 2H:1V and bottom widths typically 2 feet.

For swales with underdrains, the underdrain section is lined with filter fabric, backfilled with washed #57 stone and have a 6” PVC perforated pipe underdrain installed.

A structural bioswale was developed to accommodate residents that park in the right-of-way areas where bioswales were proposed. The structural bioswale is similar to the nonstructural bioswales except that they have a 0.5 foot layer of 2 to 6 inch cobble and C-33 sand (with limited fines) placed over the deep disked organic layer.

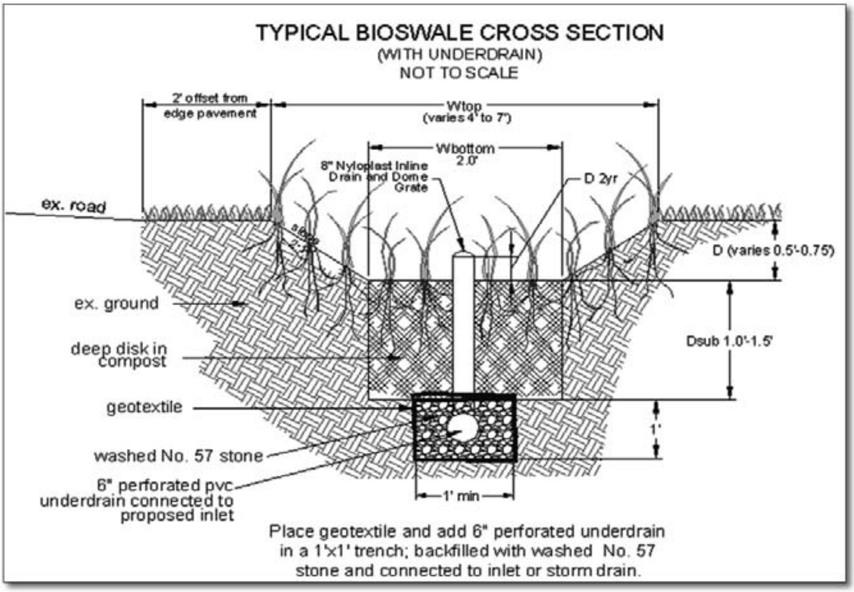


Figure 3. Typical Bioswale Cross Section

Bioswale Costs

The estimated cost per linear foot for each of the bioswale types is summarized below (this takes into account the engineer’s estimate as well as the unit bid prices):

Bioswale without underdrain	*$20/LF*
Bioswale with underdrain	*$50/LF*
Structural Bioswale without underdrain	*$40/LF*
Structural Bioswale with underdrain	*$60/LF*

Quantifying the Benefits of the Bioswales

The Bioswales have two major hydrologic benefits resulting in decreased peak discharges. The first is the attenuation which increases the time of concentration (Tc). The second is the storage volume provided. The storage volume benefits were modeled using a modified Reduced Curve Number method. Using the methods decribed below the Tc with the addition of the bioswales along Fontron increased to more than an hour, which significantly reduces peak discharge. The storage provided in the bioswales achieves the target volumes to reduce the RCNs to woods in good condition.

The Tc increase quantification was performed using the following method: (1) Compute the runoff delivery to the bioswale as Volume Runoff in cubic feet (for the subarea draining to the swale) over a 24 hour period assuming a linear distribution (Volume runoff divided by 24 hours), this is the filling rate of the swale in cubic feet per hour; (2) Determine the surface ponding volume (Area of the Swale times the surface ponding depth); (3) Determine the time required to fill surface ponding (Surface ponding volume in cubic feet divided by the filling rate in cubic feet per hour; (4) Calculate the velocity in the bioswale prior to overflow (Length of the swale divided by the time to fill the swale in seconds); and (5) Input the velocity into TR-55 to compute the time of concentration. The Bioswales along Fontron in the upper portion of the longest travel path result in increasing the Tc to more than an hour.

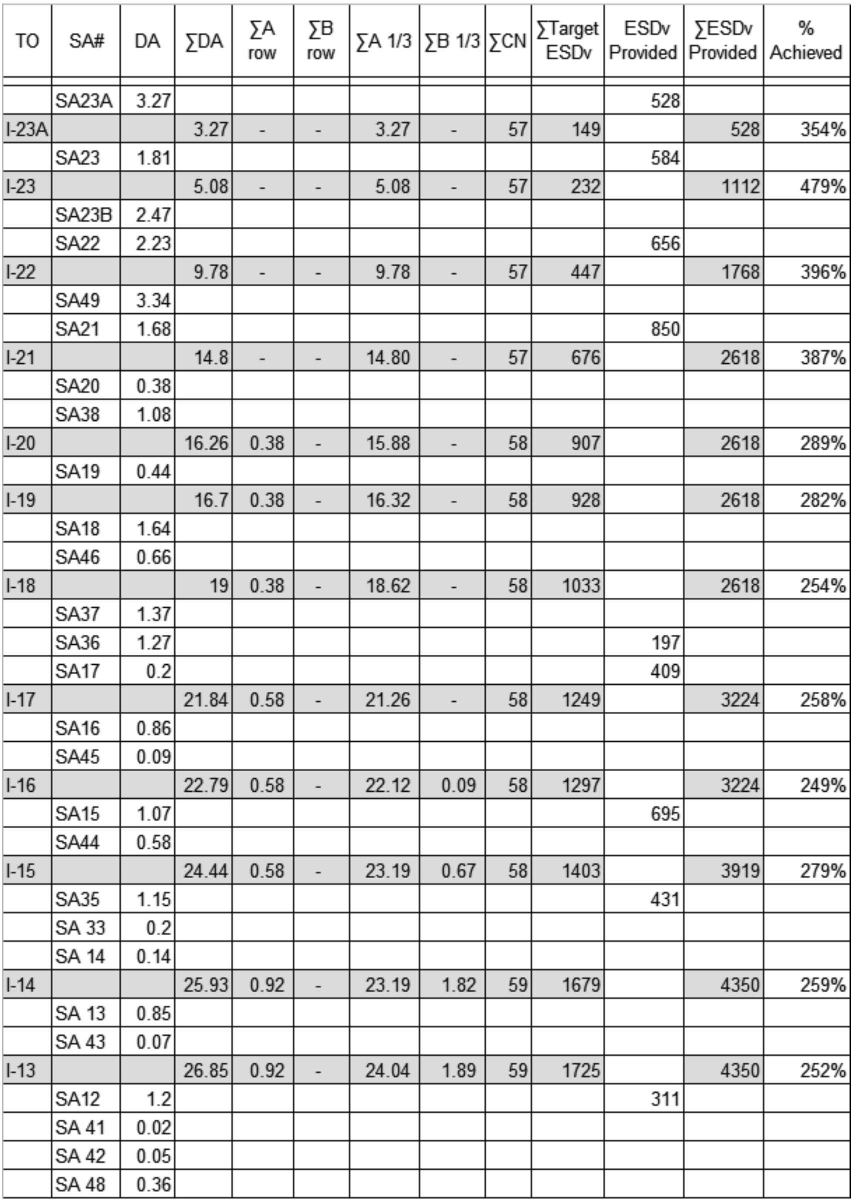
The Reduced Curve Number approach was used to compute the ESD/LID volume necessary to treat the 1” rainfall to achieve the hydrology of ‘woods in good condition’ (i.e. RCN of 44). Table 3 shows the hydrology summary table with additional columns showing the computed target volumes required to reduce the RCNs to 44, the volumes provided, and the percent ESDv achieved. Volumes assume 40% voids in the subgrade material and surface volume to the 2-year ponding depth (summarized in Table 2).

Conclusions

The Selby on the Bay community experiences frequent flooding due to lack of storm water management, proximity of the water table, and low-lying areas. Narrow right-of-ways and existing infrastructure and utilities (specifically sanitary sewer lines and electric poles) limit the options (vertically and horizontally) for swales and storm drain pipes. Surprisingly high infiltration rates based on in-situ testing provide opportunities to employ bio-swales, which provide water quality benefits and reduce peak discharge.

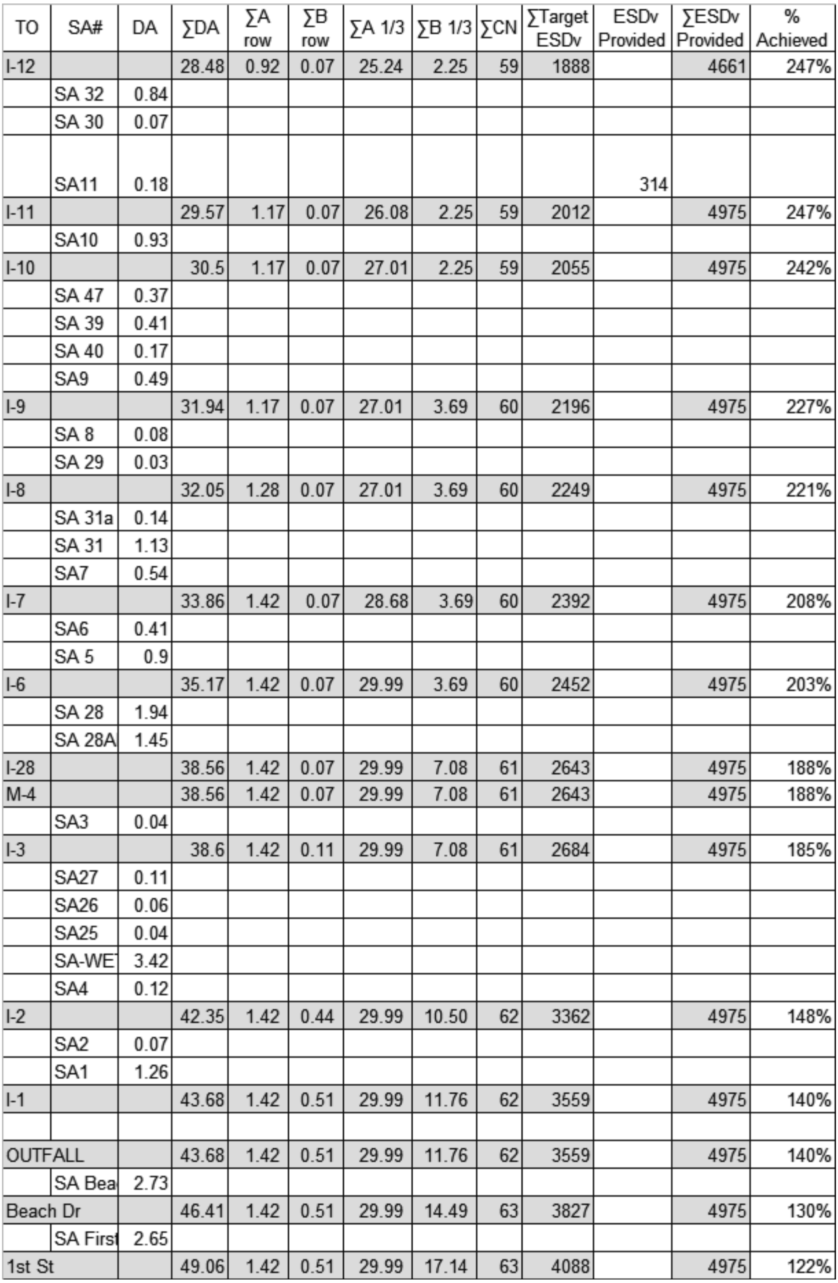
Innovative bioswale construction specifications including in-situ soil enhancements and structural bioswales were developed. The in-situ technique reduces construction cost and disturbance. The structural bioswales accommodate the desire for residents to continue parking along the roadside

Table 3. Hydrology Summary Table with ESDv



TO	SA#	DA	∑DA	∑A row	∑B row	∑A 1/3	∑B 1/3	∑CN	∑Target ESDv	ESDv Provided	∑ESDv Provided	% Achieved
	SA23A	3.27								528		
I-23A			3.27	-	-	3.27	-	57	149		528	354%
	SA23	1.81								584		
I-23			5.08	-	-	5.08	-	57	232		1112	479%
	SA23B	2.47										
	SA22	2.23								656		
I-22			9.78	-	-	9.78	-	57	447		1768	396%
	SA49	3.34										
	SA21	1.68								850		
I-21			14.8	-	-	14.80	-	57	676		2618	387%
	SA20	0.38										
	SA38	1.08										
I-20			16.26	0.38	-	15.88	-	58	907		2618	289%
	SA19	0.44										
I-19			16.7	0.38	-	16.32	-	58	928		2618	282%
	SA18	1.64										
	SA46	0.66										
I-18			19	0.38	-	18.62	-	58	1033		2618	254%
	SA37	1.37										
	SA36	1.27								197		
	SA17	0.2								409		
I-17			21.84	0.58	-	21.26	-	58	1249		3224	258%
	SA16	0.86										
	SA45	0.09										
I-16			22.79	0.58	-	22.12	0.09	58	1297		3224	249%
	SA15	1.07								695		
	SA44	0.58										
I-15			24.44	0.58	-	23.19	0.67	58	1403		3919	279%
	SA35	1.15								431		
	SA 33	0.2										
	SA 14	0.14										
I-14			25.93	0.92	-	23.19	1.82	59	1679		4350	259%
	SA 13	0.85										
	SA 43	0.07										
I-13			26.85	0.92	-	24.04	1.89	59	1725		4350	252%
	SA12	1.2								311		
	SA 41	0.02										
	SA 42	0.05										
	SA 48	0.36										

Table 3. Hydrology Summary Table with ESDv (continued)



TO	SA#	DA	∑DA	∑A row	∑B row	∑A 1/3	∑B 1/3	∑CN	∑Target ESDv	ESDv Provided	∑ESDv Provided	% Achieved
I-12			28.48	0.92	0.07	25.24	2.25	59	1888		4661	247%
	SA 32	0.84										
	SA 30	0.07										
	SA11	0.18								314		
I-11			29.57	1.17	0.07	26.08	2.25	59	2012		4975	247%
	SA10	0.93										
I-10			30.5	1.17	0.07	27.01	2.25	59	2055		4975	242%
	SA 47	0.37										
	SA 39	0.41										
	SA 40	0.17										
	SA9	0.49										
I-9			31.94	1.17	0.07	27.01	3.69	60	2196		4975	227%
	SA 8	0.08										
	SA 29	0.03										
I-8			32.05	1.28	0.07	27.01	3.69	60	2249		4975	221%
	SA 31a	0.14										
	SA 31	1.13										
	SA7	0.54										
I-7			33.86	1.42	0.07	28.68	3.69	60	2392		4975	208%
	SA6	0.41										
	SA 5	0.9										
I-6			35.17	1.42	0.07	29.99	3.69	60	2452		4975	203%
	SA 28	1.94										
	SA 28A	1.45										
I-28			38.56	1.42	0.07	29.99	7.08	61	2643		4975	188%
M-4			38.56	1.42	0.07	29.99	7.08	61	2643		4975	188%
	SA3	0.04										
I-3			38.6	1.42	0.11	29.99	7.08	61	2684		4975	185%
	SA27	0.11										
	SA26	0.06										
	SA25	0.04										
	SA-WE	3.42										
	SA4	0.12										
I-2			42.35	1.42	0.44	29.99	10.50	62	3362		4975	148%
	SA2	0.07										
	SA1	1.26										
I-1			43.68	1.42	0.51	29.99	11.76	62	3559		4975	140%
OUTFALL			43.68	1.42	0.51	29.99	11.76	62	3559		4975	140%
	SA Bea	2.73										
Beach Dr			46.41	1.42	0.51	29.99	14.49	63	3827		4975	130%
	SA Firs	2.65										
1st St			49.06	1.42	0.51	29.99	17.14	63	4088		4975	122%

Innovative methods of quantifying the benefits of the LID retrofit using bioswales were employed. The attenuation benefits of the bioswales along Fontron in the upper portion of the longest travel path result in increasing the Tc to more than an hour. The storage provided by the swales successfully achieves the target of woods in good condition as shown with the Reduced Curve Number method.

The bioswale LID retrofit for Selby on the Bay can be applied in many coastal Bay communities to improve drainage and water quality. These retrofit opportunities will be a key to achieving the now required pollutant reductions and water quality improvements in the Bay.

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The City of Richmond's Green Alleys Program:
A Tale of Two Alleys

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Abstract

They were the best of alleys, they were the worst of alleys… the following paper tells the story of the City of Richmond's Green Alley Program pilot projects. Design details, challenges, and lessons learned are included to help inform and improve the practice of permeable alley retrofits.

Introduction

Like many other long-standing urban centers, the City of Richmond, Virginia still has areas in which storm and sanitary flows are carried by a combined sewer system (CSS). Unfortunately, these systems can be overwhelmed during rainfall events causing combined sewer overflows (CSO) and negatively impacting wastewater treatment plants. Limiting CSO events is a priority for the Richmond Department of Public Utilities; and, implementing green infrastructure practices can help in this mission by reducing wet weather flows that threaten existing pipe capacity.

In partnership with the National Fish and Wildlife Foundation (NFWF) and the Virginia Department of Conservation and Recreation (DCR), the City of Richmond installed two green alleys as pilots for a Green Alley Program modeled after Chicago's successful alley renovation program. Since the program's inception in 2006, Chicago has recorded significant benefits from the conversion of traditional, impervious alley surfaces to permeable pavement sections in their CSS areas. As part of a larger "Greening the Capital" initiative, the City of Richmond chose the prominently located 5th Street and 12th Street alleys for permeable pavement retrofits; thereby incorporating multi-functional stormwater management measures in the densely developed urban core.

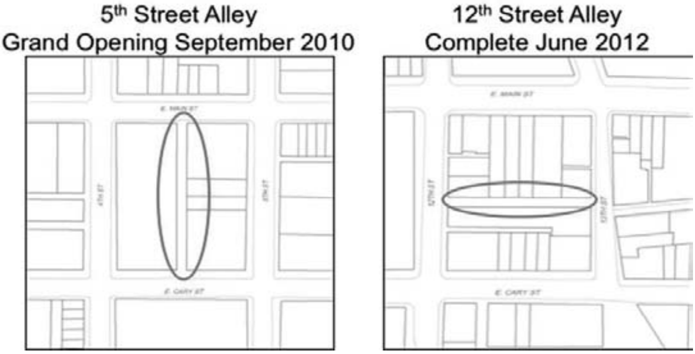

Figure 1: Green Alley Pilot Project Locations

Green Alley Form and Function

Green alleys are an effective stormwater management measure in which an alternative pavement section provides pollutant removal benefits in addition to runoff volume reduction, peak flow attenuation and storm peak delay. Storm runoff is stored in the reservoir section of the permeable pavement and released at a trickle to reduce stress on the capacity of receiving systems. They are appropriate for a wide variety of development scenarios, can be installed with liners in groundwater sensitive areas, and are especially beneficial in locations with limited capacity pipes such as CSS areas.

The elements of a typical green alley pavement section include a permeable top layer over a reservoir layer that is sized to handle pavement loading needs as well as stormwater treatment goals. The permeable top allows water to percolate into the reservoir layer, thereby reducing surface runoff and localized flooding. This layer also serves as a pre-treatment measure, capturing silt and trash for easy maintenance with vacuum sweepers. Several options for permeable surfaces are available, including porous asphalt, pervious concrete, and a variety of interlocking concrete pavers. The stone reservoir layer is typically #2 or #3 stone with capacity to handle peak flow management and infiltration storage (if appropriate) while providing opportunity for pollutant removal through biological activity.

A Tale of Two Alleys: Design Constraints and Challenges

The two pilot alleys in the Richmond Green Alley Program were chosen for their visibility and prominent locations as well as their existing state of disrepair and history of drainage complaints. Looking at the existing conditions pictures below, one can begin to see the readily apparent design constraints: steep longitudinal and cross-sectional slopes, existing garage entrances, streetlights and overhead power. Underground constraints in both alleys included existing gas lines, utility duct banks, and adjacent basements, as well as an existing sanitary line in 12th Street Green Alley.

Picture 1: 5th Street Existing Conditions

Picture 2: 12th Street Existing Conditions

The 5th and 12th Street alleys were lined due to concerns that water would migrate into adjacent basements; and, the stone reservoir section was stepped and underdrained to create multiple flat bottomed cells. The cells were modeled as interconnected ponds with the goal of reducing 1-year peak flows and containing the 10-year storm within the stone reservoir. For installations with infiltration goals, a flat bottomed stone reservoir is imperative: stepping the reservoir layers also protects against undercutting due to flow velocities along a sloped bottom, maximizes the efficiency of the stone storage layer, and reduces “pavement pumping” in which water from the upslope section flows back out of downslope areas (note: overflow drains may be required to address pumping concerns).

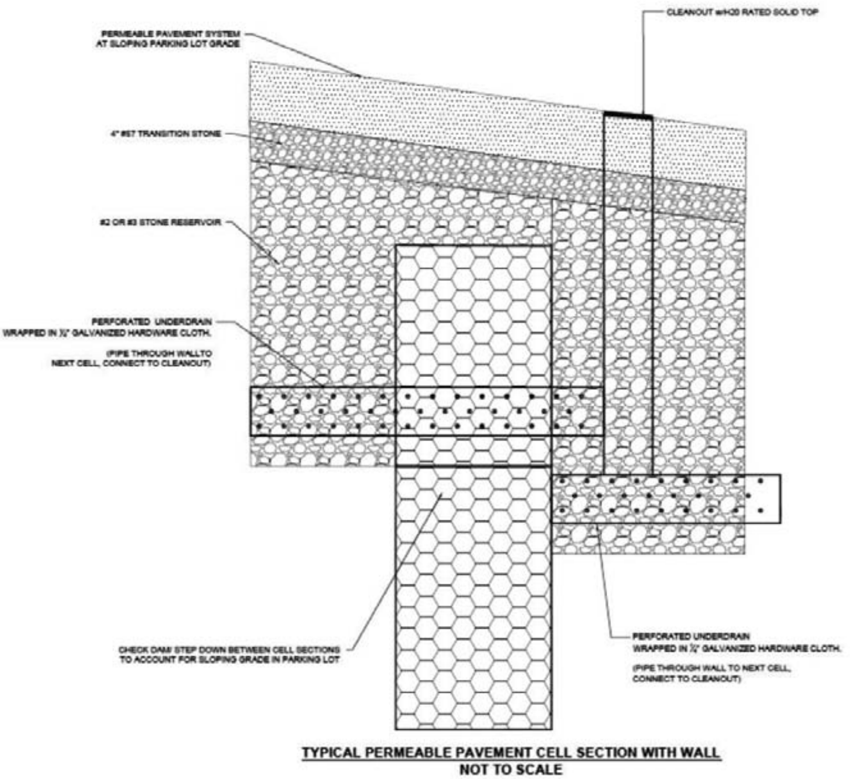

Figure 2: Stepped Stone Reservoir Cells

The existing cobblestone was an unexpected design constraint in that the architectural review board and urban design committees were concerned with maintaining the historic aesthic of the cobblestone and wanted the original cobblestone sections restored. Educational presentations at the public meetings helped alleviate misconceptions that cobblestone alleys are porous and highlighted the stormwater management benefits of the permeable pavement sections. Ultimately, an interlocking concrete paver system with tumbled, gray, cobble-like pavers was chosen and has become the standard within the City rights-of-way. Added benefits of the interlocking concrete paver system for green alley installations include durability against trash truck movements and underground utility access without the danger of impervious trench patches.

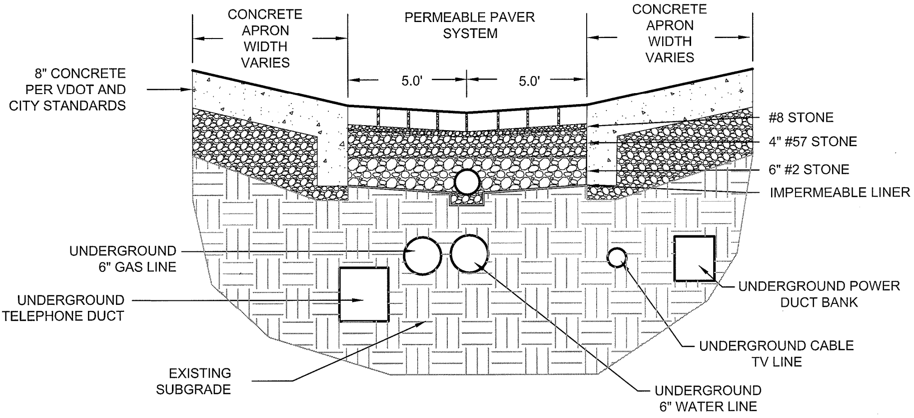

Figure 3: 12th Street Alley Section

Alleys in the City of Richmond typically contain water, sewer, and/or gas service lines in addition to power and communication lines. We have found coordination with utility services to be the greatest challenge in the design and construction of the City's green alley retrofit projects. An alley retrofit project is an opportunity to upgrade aging water, sewer, and gas services, as well as to put overhead utilities underground; however, these upgrades can significantly impact the cost of the project. Utility work and alley construction went very smoothly with the 5th Street alley. However, the 12th Street alley construction was plagued by conflict coordination issues and delays, from a mis-placed sanitary sewer upgrade to the discovery of an unrecorded wooden telephone duct bank.

Annecdotally, when preparing the operation and maintenance guideline section for restoring the alley after utility maintenance, we (Timmons Group) called Chicago to discuss any relevant lessons learned during maintenance in their alleys. They were quick to inform us that their alleys tend to be free of utilities. *We are officially jealous!*

Lessons Learned

Choose retrofit locations wisely. Target locations with the greatest stormwater benefit and need, but also weigh those choices against existing utilities, previously scheduled maintenance, and private access needs. If possible, have frank conversations across municipal departments regarding cost sharing for service and utility upgrades.

Begin with a comprehensive survey. Underground utility survey, including several pot-holes for vertical locations, in addition to a topographic survey is the key to success for many of our urban retrofit projects. Especially given the limited space of the green alley projects, identifying impacts and utility coordination needs early in the process will ensure accurate budgets and smooth construction.

Don't forget the dry utilities. Will your power company need to hold poles, install conduit, or interrupt service? Who is responsible for the street lights? How many communication companies have lines in your alley and what are their pole/conduit sharing agreements? If possible, try to get all of the players together to discuss potential impacts and coordination, the need for multiple contractors and whether or not they can share the site both during design and to kick-off construction.

Consider stakeholder issues and inconveniences. During construction of the 5th Street Alley, trash truck access was blocked: the contract documents included provisions requiring the contractor to transport trash to the ends of the alleys on collection days. Access to a private business garage was temporarily blocked at 5th Street; however, the owners had bought into the project and were very supportive. Blocking access to an apartment building garage at 12th Street was met with less enthusiasm from residents: the City paid for alternative parking provisions during the life of the project and staged construction to reopen access as quickly as possible. Public communication both during design and during construction is essential.

Program Expansion

The two pilot projects have been successfully completed and are functioning beautifully. Additional alley retrofits near Monument Avenue, St. Christopher's School, and at the campus of VCU have also been completed as the Green Alley Program expands. The following pictures highlight 3 of the completed projects:

Picture 3: 5th Street Alley

Picture 4: 12th Street Alley

Picture 5: Monument Avenue Pre-thru Final

Nitrate in Green Roof Runoff

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Abstract

This study investigated the mass and concentration of nitrate in the runoff from black EPDM membrane (control) roofs, modular green roof units, and built-in-place (BIP) green roof models. Results for mass and concentration were similar. Results indicated that the mean nitrate mass in the runoff from the green roof systems was statistically higher than from the control roofs and that the mass from the planted BIP systems was statistically greater than from the unplanted systems. The mean nitrate mass in the runoff of the BIP models decreased as depth increased, requiring at least 15 cm to meet a 10 ppm limit. The mean mass from the 10-cm planted BIP models was statistically less than from the 10-cm modular units, apparently as a result of the drainage layer in the BIP system. The 5-cm planted BIP system was statistically similar to the modular system, even though the modular system provides better plant performance. Despite continued fertilization, the nitrate mass in the planted BIP models decreased over time, likely as a result of the degradation of the organic fraction of the growth media.

Introduction

The increase in the global population has increased urban development, which has increased the amount of impervious surfaces. While the construction of impervious structures is on the rise, natural infiltration through farmland, parks, and forests has been drastically reduced. Green technology has become an appealing way to offset the reduction of natural infiltration, thus reducing the amount of storm water runoff in urban areas and potentially improving the quality of the runoff.

Green roofs are one technology being investigated to improve the quality of the urban environment. Green roofs are commonly constructed of four layers—drainage material, filter preventing the loss of growth media particles, growth media substrate and vegetation. The thickness and type of the growth media layer and the type of vegetation are all key components when designing a green roof system.

Green roofs are typically divided into two main engineering categories: intensive and extensive. Intensive green roofs are established with deep soil layers (at least 30 cm); they can support deep rooting plants and typically require maintenance in the form of weeding, fertilizing, and watering. Extensive vegetated roofs are established with thin soil layers (less than 30 cm, typically 5 – 15 cm). They are planted with shallower rooting plants that are expected to provide full coverage of the vegetated roof. Extensive vegetated roofs are designed to be low maintenance, typically requiring limited fertilization and irrigation.

One way that green roofs function is by reducing runoff. The reduction consists in delaying the initial time of runoff due to the absorption of water in the green roof, reducing the total runoff by retaining part of the rainfall and distributing the runoff over a longer time period through a relatively slow release of the excess water that is stored in the substrate layer (Mentens et al., 2006). The amount retained depends on many factors, such as the volume and intensity of the rainfall, the amount of time since the previous rainfall event, the depth and wetting scale of the substrate layer and the slope of the roof (Liptan, 2003).

Green roofs may potentially reduce the pollution of urban runoff by absorbing and filtering pollutants, but they can also potentially contribute to pollutants released into water from the soil, plants and fertilizers. The quality of runoff from a green roof depends on the type of the roof (the thickness of the substrate layer, its composition, vegetation and the type of drainage), the age of the roof, its maintenance and also on the type of the surrounding area and the local pollution sources (e.g., Berndtsson, 2010 and Alsup et al., 2010). For most analyses on storm water runoff, the results differ based on the green roof vegetation and the media used. Monterusso et al. (2004) studied effluent runoff from green roofs with herbaceous perennials to those growing sedum and found that nitrate concentrations in the runoff were higher from the sedum roofs and that concentration levels were higher in shallower growth media depths. Moran et al. (2003) showed that compost in the substrate layer may cause high concentrations of nitrogen in green roof runoff. However, Berndtsson et al. (2006) studied green roofs that behave as a sink for nitrate nitrogen and reduced ammonium nitrogen and total nitrogen. In Michigan, Carpenter and Kaluvakolnu (2011) compared runoff from asphalt, gravel ballasted, and extensive green roofs and reported that green roofs had no significant differences for nitrate concentrations. However, mean mass values for nitrate from the green roof were lower than from the asphalt roof (Rowe, 2010). In Pennsylvania, runoff from the green roofs contained a higher concentration of most of the nutrients measured relative to a conventional roof, but the concentrations were no different than what would runoff of any planted landscape at ground level (US EPA, 2009).

Fertilization is generally used to improve the growth of the plants and to achieve a desired dense vegetation cover in a reasonable time frame. The fertilizers used are most often encapsulated controlled release fertilizers, which are designed to release nutrients at a pace similar to the nutrient requirements of the vegetation, thereby reducing the risk for leaching and fertilization damage to the vegetation

(Shaviv, 2001). Emilsson et al. (2007) measured nutrient runoff, nutrient storage, and plant uptake following fertilization of vegetated sedum mats, shoot-established vegetation, and un-vegetated substrates following applications of controlled release fertilizer (CRF) or a combination of CRF and conventional fertilizer. Nutrient runoff concentrations increased when conventional fertilizers were used, and although the levels decreased over time, they were still higher than the green roofs exposed to the CRF (Rowe, 2010). The initial nutrient load likely is due to the decomposition of organic matter that was incorporated into the original fertilizer mix (Rowe, 2010). Teemusk and Mander (2007) found higher levels of nitrate in green roof runoff (0.28 – 0.8 mg/L) than in control roof runoff (0.19 – 0.4 mg/L), but the levels they found were low because fertilizer was not used.

Woods (2010) investigated nitrate concentrations in storm water runoff from green roof modules with different media depths. Her study indicated that green roofs may be a potential contributor to water pollution due to fertilizer and growing medium components. Analysis showed that nitrate concentrations were at their highest in the shallowest media depths and gradually decreased as the media depths increased. It was unclear, however, if the mass of nitrate was similar or different. Therefore, her data was reexamined in terms of mass and supplemented with additional experimental data collected in June 2011.

Materials and Methods

Experimental design of green roof systems. Green roof modules were established at the Southern Illinois University Edwardsville ground-level Environmental Sciences Field Site on September 5, 2005. The initial setup consisted of 36 model green roof systems placed in a randomized design on four tables made from treated lumber (Forrester, 2007). Four of these systems were control roofs (black EPDM membrane only), four were a modular tray system (Green Roof Blocks^{TM}), and the remaining 28 were built-in-place systems (BIPS).

Each of the BIPS was composed of a 61cm x 61cm wood frame with wafer board substrate and an attached EPDM roofing membrane (Forrester, 2007). Sheet metal edging was installed around the edges of the box to contain the growing media. Growing media was placed at 5 cm, 10 cm, 15 cm, and 20 cm depths on top of a drainage layer. For each depth, there were four BIPS that were planted and three BIPS that were left unplanted. Every BIPS had a covered guttering system that transported the runoff to a drainage hose connected to a collection container (a 5-gallon plastic gasoline can).

The four trays were the same overall dimensions as the BIPS but were made from 8 millimeter anodized aluminum and contained no drainage layer. Each had 10 cm of growing media and was planted. As rain water flowed through the system, it drained through holes in the bottoms of the model and was collected in an aluminum collection sleeve. Attached to each collection sleeve was a drainage hose that fed the runoff water to a collection container (Forrester, 2007).

The growing media used in the study was 80% by volume arkalyte (6 mm – 9 mm expanded clay) and 20% by volume composted pine bark. Each BIPS and tray was planted with five plugs of *Sedum hybridum* 'immergrauch' on September 5, 2005 (Forrester, 2007). All five sedum plugs were randomly selected and placed equidistantly from the green roof edge.

All of the planted systems were initially fertilized in September 2005 with 7.2 grams of isobutylidene-diurea (IBDU, 30% nitrogen content) per plant. IBDU is highly soluble. The first two weeks after planting, the green roof systems were irrigated. In May 2006, the planted green roof systems were fertilized again with the same type and quantity of fertilizer to support replanting after winter die-off. Unlike a typical installation, the models were fertilized annually to support various research projects that included replanting. In March of years 2007-2009 5 grams of Nutricote (540) 18-6-8 (18% nitrogen content) was applied to each plant. In March 2010 and 2011 Woodace 18-5-10 was applied to each plant. Nutricote and Woodace are time-release fertilizers. The time between application of the fertilizer and runoff collection varied based on precipitation patterns.

Analysis of storm water retention. At the end of each rain event between June 29, 2007 and April 8, 2008, each collection container was unhooked from its green roof system and weighed to determine the amount of storm water retention. Each collection container was weighed individually with the runoff and without the runoff using a Mettler Toledo SB 32000 Field Balance. The difference in the two readings was the amount of runoff for that storm period. Rainfall intensity was not collected nor considered in analyses.

Analysis of nitrate in storm water runoff. Nitrate analysis started on June 29, 2007. A composite sample of at least 100 mL was decanted from each collection container after each storm event that had a 2.5 cm rainfall amount or greater. There were a total of six such rainfall events that fell within the 2007-2008 analysis period. All samples were analyzed for nitrate concentration within a 12 hour period after collection. Samples were analyzed using a Fisher Scientific Accumet XL25 pH/mV/Ion meter with nitrate ion electrode probe. Methods described in the Fisher Scientific Accument XL25 manual were used to analyze the samples (Woods 2010).

Data was gathered in June 2011 to supplement the earlier data. Three rain events generated enough runoff to be collected from the 10-cm and 20-cm planted BIPS. Samples were collected the same way as previously explained and analysis was done within 24 hours of the collection time. All of the collected samples were taken to the American Bottoms Regional Wastewater Treatment Facility in Sauget, IL. American Bottoms is an accredited lab recognized by the National Environmental Laboratory Accreditation Program. Samples were analyzed for nitrate using an approved method derived from EPA Method 300.0 Rev 2.1 1993 and a Dionex Dx 500 Chromatography System with an AS40 auto-sampler.

All nitrate concentrations were converted to mass using the following equation.

$$\begin{aligned} nitrate\ mass\ (g) \\ &= nitrate\ conc.\left(\frac{mg}{L}\right) * \left(\frac{1\ kg}{100000mg}\right) * \left(\frac{1000L}{998.2kg}\right) \\ &* runoff\ weight\ (g) \end{aligned}$$

Pooled data were analyzed in terms of the nitrate mass and concentration in the runoff. Data were analyzed using a one-way ANOVA with a completely randomized design. A Tukey's post hoc test was used to rank the differences at an alpha level of 0.05. All statistical analyses were completed using Minitab 16.

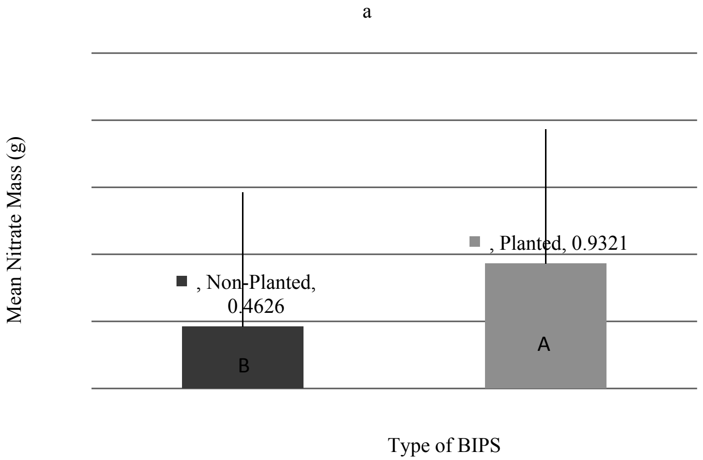
Results and Discussion

The mean nitrate mass and concentration in planted BIPS were statistically different from non-planted BIPS (Figure 1). The fertilizer in the planted models increased nitrate in the runoff by approximately two. The nitrate from non-planted models is likely from the composted pine bark.

The mean nitrate mass found in the runoff of most of the BIPS was significantly higher than that found in the runoff from the control (EPDM) roofs (Figure 2a). The results for concentration were similar (Figure 2b). The likely source of nitrate from the control roofs was atmospheric deposition.

The mean nitrate mass and concentration from the BIPS decreased with increasing depth (Figure 2). This decrease in nitrate levels could be due to the larger media volume available to sorb or convert the nitrate, longer retention times, less time under saturated conditions, or better plant performance. In non-planted BIPS, the effect of growth media depth was much smaller (Figure 3), indicating that plant performance is key. Woods (2010) found statistically poorer plant performance in the 5-cm depth and statistically similar plant performance in the other depths.

The mean nitrate mass and concentration in the runoff from the modular system was higher than from the 10-cm BIPS and the control roof (Figure 4). There are two primary differences between the 10-cm planted BIPS and the modular system. One, the BIPS has a drainage layer. Two, the BIPS are made of Galvalume, which is a 55% aluminum-zinc coated steel, while the modular units are made of anodized aluminum. The metal is unlikely to affect the nitrate. The drainage layer, on the other hand, allowed the plants in the 10-cm BIPS to grow larger, resulting in greater than 99% average coverage in the BIPS versus 87% average coverage in the modular system (Woods 2010).



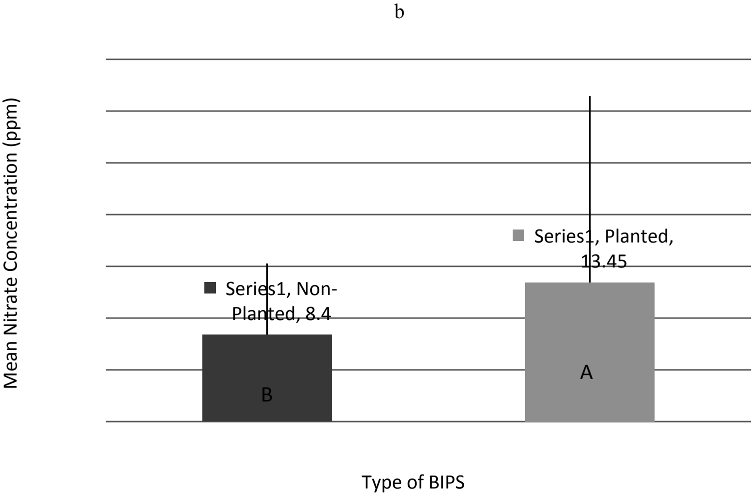
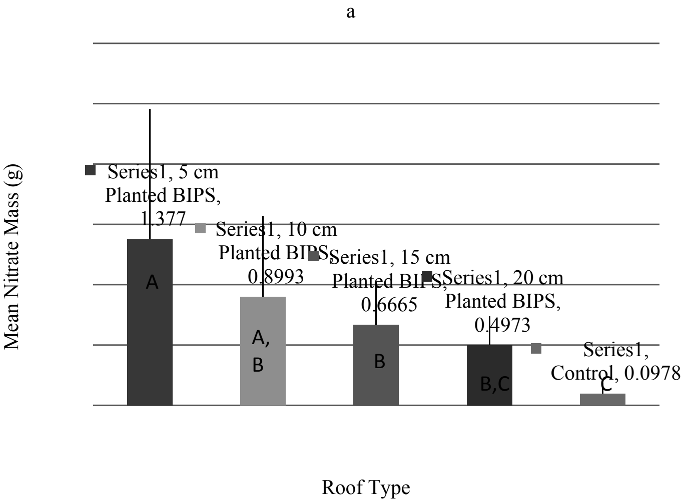


Figure 1. Mean nitrate mass (a) and concentrations (b) for rain events >2.5 cm in 2007-2008 for non-planted and planted built-in-place systems. (Bars with same letter are not significantly different at the p <0.5 level. Error bars ±1 std.dev.)



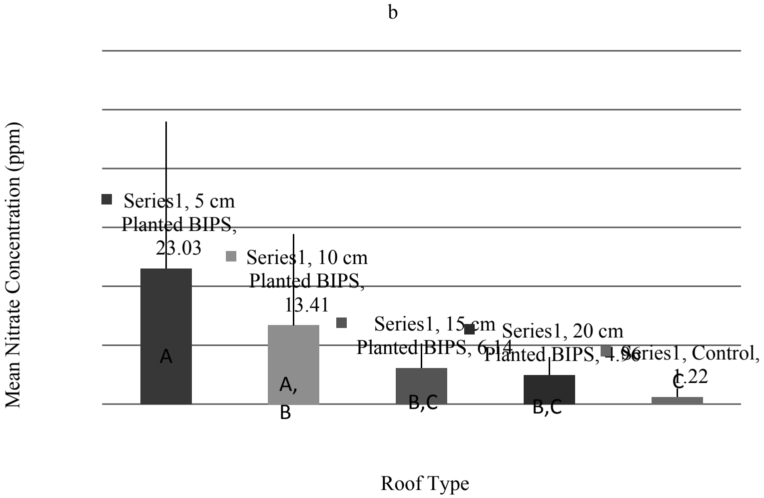


Figure 2. Mean nitrate mass (a) and concentrations (b) for rain events >2.5 cm in 2007-2008 for planted built-in-place systems with different media depths. **(**Bars with same letter are not significantly different at the p <0.5 level. Error bars ±1 std.dev.**)**

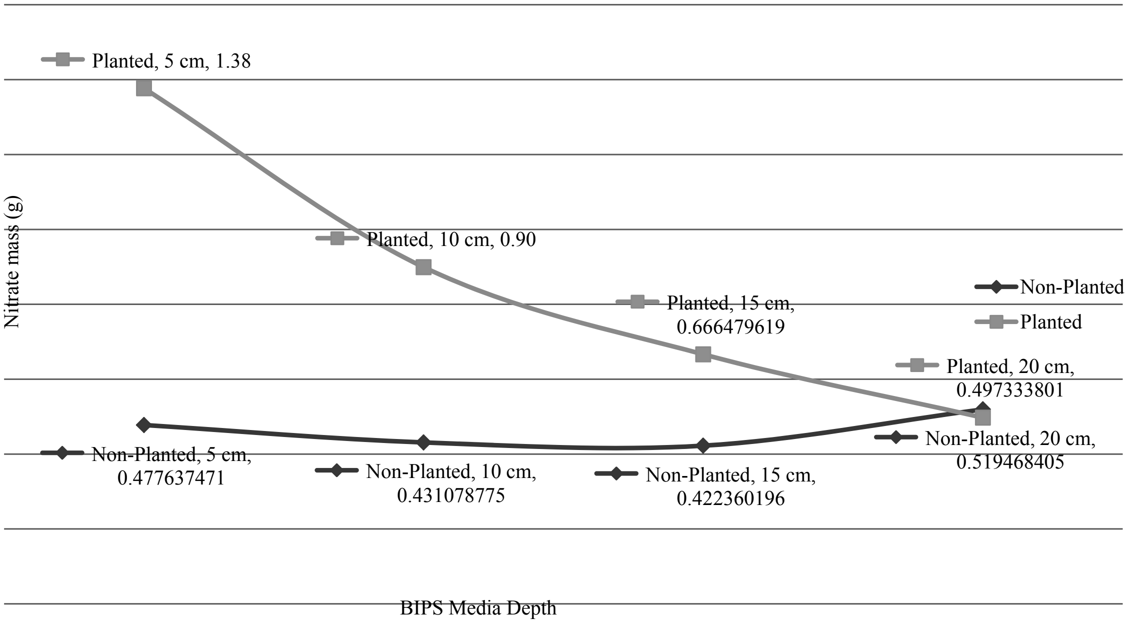
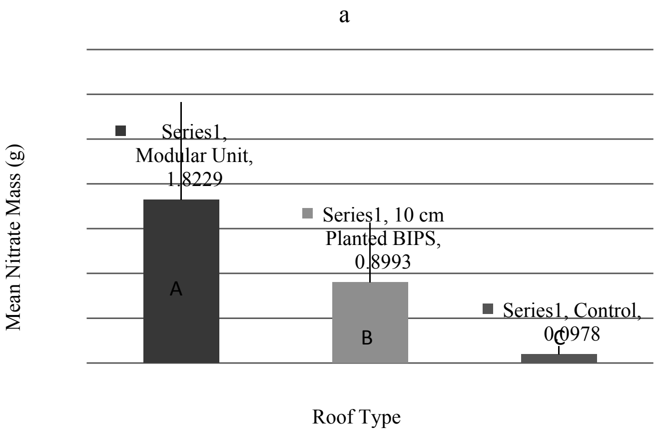


Figure 3. Mean nitrate mass for rain events >2.5 cm in 2007-2008 for 5,10, 15 and 20 cm media depths in planted and non-planted built -in-place system green roofs.



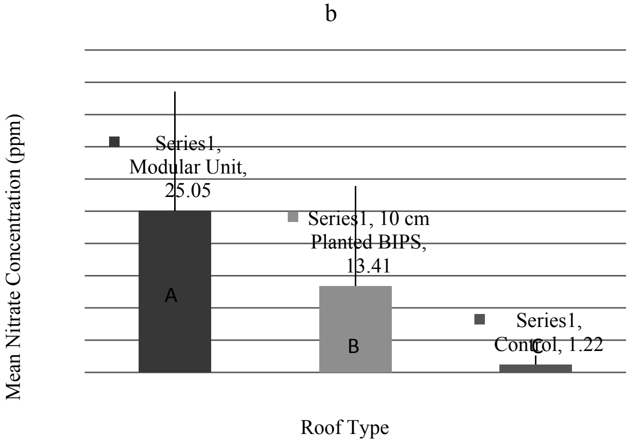


Figure 4. Mean nitrate mass (a) and concentrations (b) for rain events >2.5 cm in 2007-2008 for 10 cm built-in-place system roofs, modular units, and control roofs. (Bars with same letter are not significantly different at the p <0.5 level. Error bars ±1 std.dev.

The mean nitrate mass and concentration in the runoff from the 5-cm BIPS was statistically the same as from the modular unit (Figure 5). The drainage layer was unable to overcome the effects of the shallow growth media depth in the 5-cm BIPS, which had 78% plant coverage (Woods 2010). Despite the additional plant coverage, the modular system was unable to reduce the nitrate below the levels from the 5-cm BIPS, unlike the effect in the 10-cm BIPS. Therefore, it appears that the drainage layer itself is retaining or converting the nitrate.

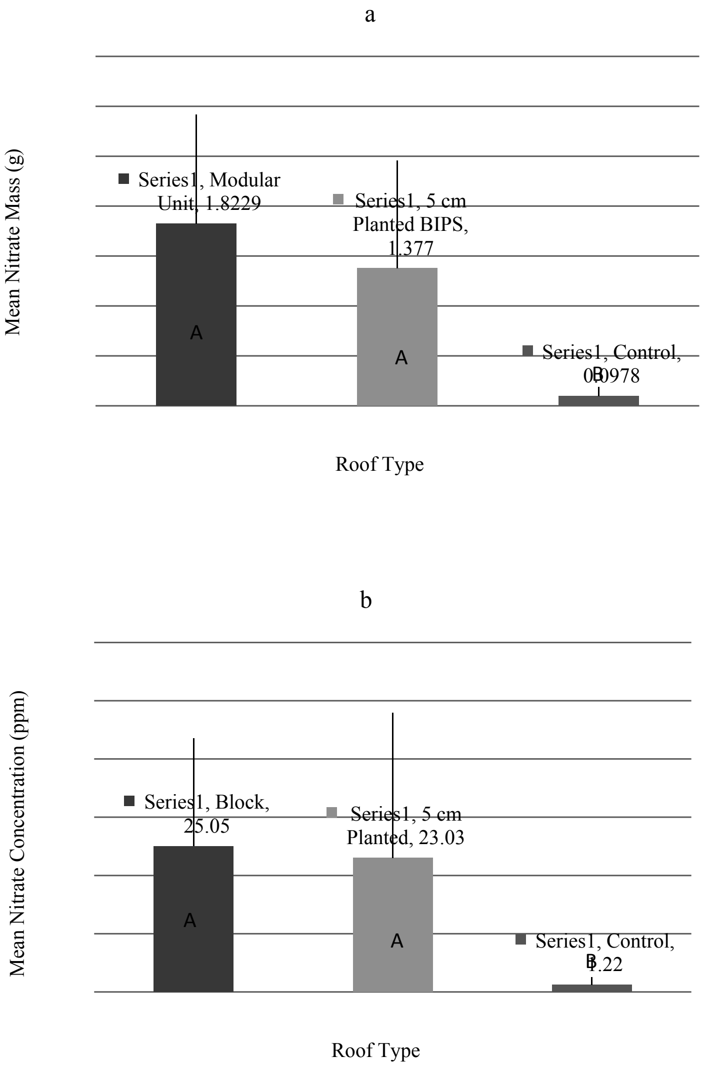


Figure 5. Mean nitrate mass (a) and concentrations (b) for rain events >2.5 cm in 2007-2008 for 5 cm built-in-place system roofs, modular units, and control roofs. (Bars with same letter are not significantly different at the p <0.5 level. Error bars ±1 std.dev.)

In June 2011, storm water was collected from 10-cm and 20-cm planted BIPS after three rain events. The mean nitrate mass and concentrations in the 10-cm BIPS were higher than the 20-cm BIPS, the same as in 2007 and 2008. Both the 10-cm and 20-cm planted BIPS average mean nitrate masses were lower than in 2007-2008 (Figures 6 and 7) despite the annual fertilization, indicating that green roof age (i.e., plant growth and growth media changes are important factors influencing nitrate in the runoff.

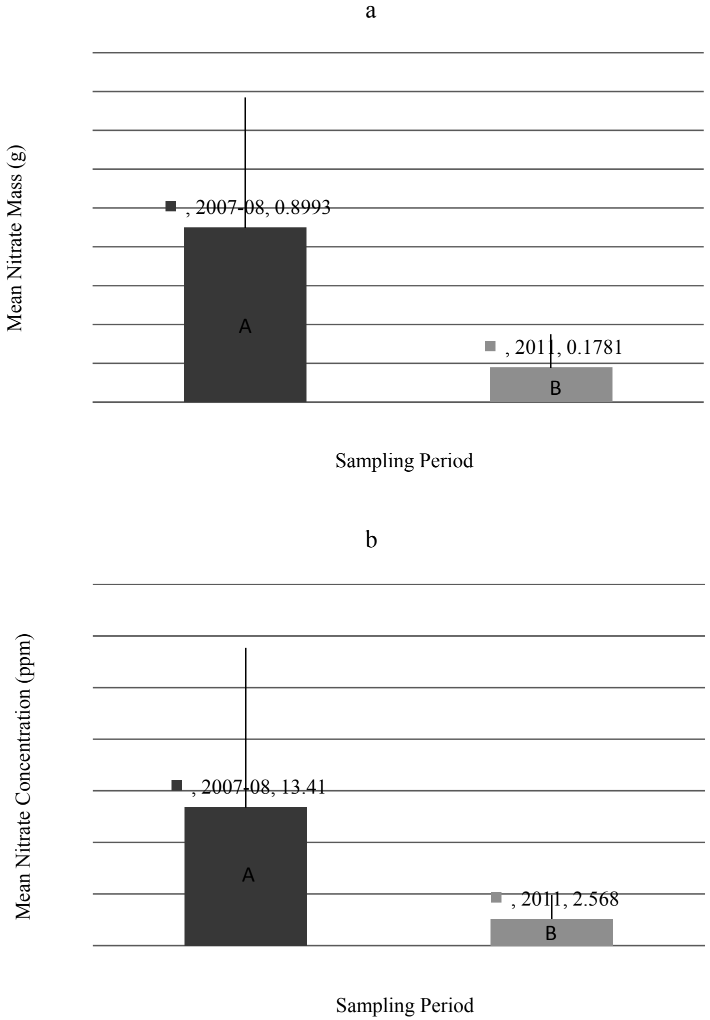


Figure 6. Mean nitrate mass (a) and concentrations (b) in 10cm built-in-place systems for rain events >2.5 cm in 2007-2008 and in June 2011. (Bars with same letter are not significantly different at the p <0.5 level. Error bars ±1 std.dev.)

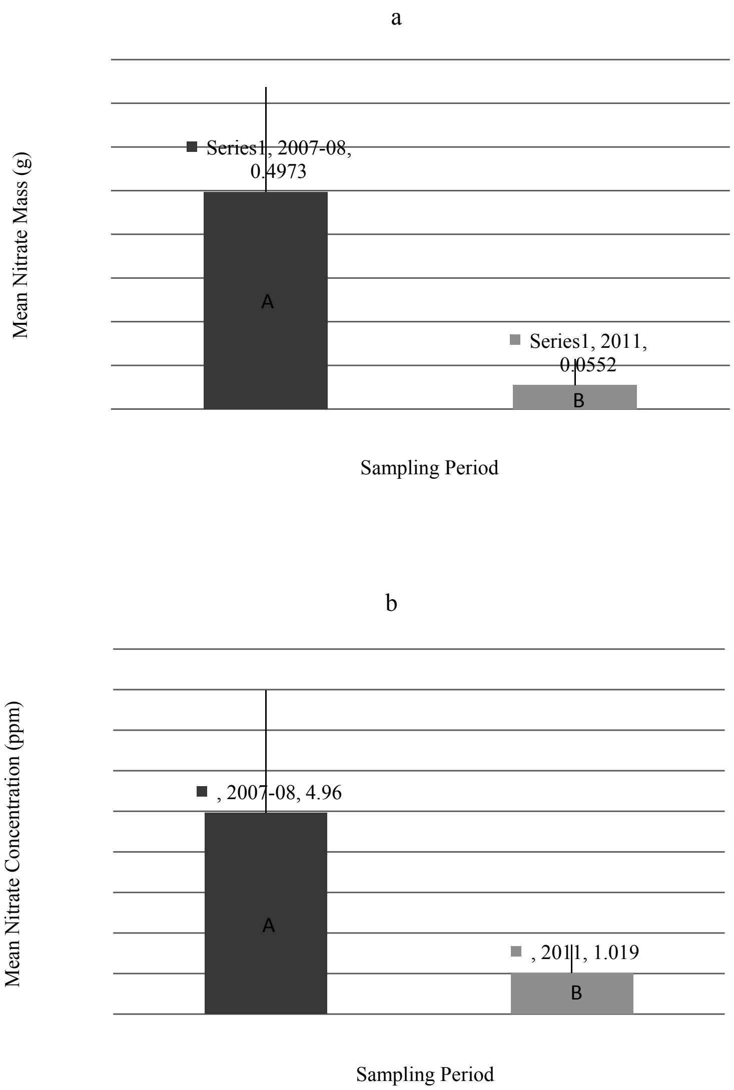


Figure 7. Mean nitrate mass (a) and concentrations (b) in 20 cm built-in-place systems for rain events >2.5 cm in 2007-2008 and in June 2011. (Bars with same letter are not significantly different at the $p < 0.5$ level. Error bars ±1 std.dev.)

Currently, there are no water quality standards for nitrate mass or concentration in urban storm water runoff. However, 10 ppm, the USEPA drinking water standard, has been used for total maximum daily load requirements for nitrate in some watersheds (e.g., Zollner Creek in Oregon and Muddy Creek/Dry River in Virginia), so it can be used for comparison purposes for runoff water quality. The average nitrate concentration in the runoff from the control roofs was 1.22 ppm, well below 10 ppm (Figure 8). (However, the control roof average was equal to the suggested discharge limit of 0.3 mg/L as nitrogen for wastewater treatment plants in the Mississippi Atchafalaya River Basin, which is set to reduce the hypoxic zone in the Gulf of Mexico.) The 15 and 20-cm planted BIPS showed slightly higher results at 6.14 and 4.96 ppm but still fell well below the limit. The 10-cm planted BIPS fell just above the standards at 13.41 ppm in 2007-2008, but in June 2011 the average nitrate concentration (2.59 ppm) fell below the standard. The 5-cm planted BIPS and modular system had average nitrate concentrations in 2007-2008 of 23.03 ppm and 25.05 ppm, respectively, falling well outside of limit.

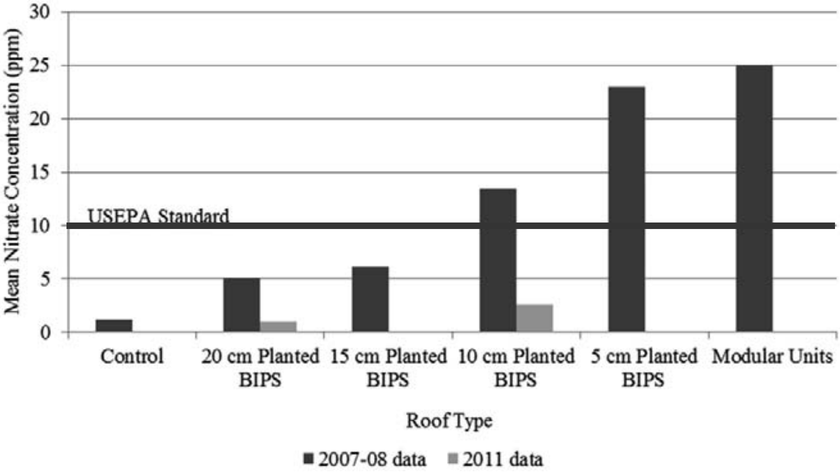


Figure 8. Mean nitrate concentrations for rain events >2.5 cm in 2007-2008 and in June 2011.

Conclusions

The overall goal in green roof design is decrease the amount of storm water runoff without jeopardizing the overall water quality. High nitrate concentrations in waterways are a concern in some regions, so reducing the amount potentially added to watersheds from green roof runoff is important. This study demonstrated that runoff quantities are irrelevant when evaluating the relative effect of the green roof models on the amount of nitrate. Concentration and mass data gave the same trends, unlike the study by Rowe (2010) that found differences.

The results of this study clearly show that the growth medium depth with the subsequent improved plant performance affect the amount of nitrate in the runoff. Increased depth results in decreased nitrate in the runoff. Monterusso et al. (2004) reported similar results. Of course, the additional weight of a deeper roof must be considered for individual installations. Based on nitrate levels found in this study, the 15-cm BIPS would be the green roof system of choice.

The study also shows that the presence or absence of a drainage layer affects the amount of nitrate in the runoff. This result appears to be due to the positive effect of the drainage layer on plant growth as well as physical or chemical reactions within the drainage layer.

The data show that the overall nitrate levels in the BIPS decrease over time, despite continued fertilizer application. Therefore, an established green roof system can improve the overall performance of the system by filtering and absorbing incoming pollutants.

Overall, green roofs can present a positive influence on water quality. However, water quality during design of the roof, particularly selection of the type and depth of growth media, needs to be considered. In addition, fertilization during establishment must be monitored to ensure that the amount of nitrate in the runoff is kept to an acceptable level.

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Vegetated Roof Systems, a Review of the Benefits and Design Features of Tray Systems and Built Up Systems

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Abstract

There are two primary approaches to green roof construction, those being termed tray systems and built-up systems. In general, tray systems use a series of plastic trays placed upon the roof like "tiles" while built up systems are comprised of rolls or large tiles of geotextiles which served to function as a drainage layer, root barrier and water retention layer.

This paper provides a narrative comparison of the two different types of approaches based on common green roof design elements. These elements include, water retention, weight, installation, etc.

Introduction

Though researched for many years, the use of vegetated roofs or Eco roofs has not, until recently, become a mainstream stormwater control measure. With the increased focus on Low Impact Development (LID) which emphasizes volume reduction of stormwater runoff as well as water quality, the use of technologies which reduce runoff though processes of evapotranspiration, infiltration and harvesting for beneficial use are becoming increasing popular. This approach, as a means of achieving both water quality and quantity goals established by jurisdictions throughout the United States is becoming more critical given the need to meet tightening federal regulations stemming from the Clean Water Act.

There are two primary approaches to Eco roof construction, those being termed tray systems and built-up systems. In general, tray systems use a series of plastic trays placed upon the roof like "tiles" while built up systems are comprised of rolls or large tiles of geotextiles which served to function as a drainage layer, root barrier and water retention layer.

Like any technology, both of these system offer features and benefits that may favor one over the other when looking at the specific design issues and considerations for a particular site. This paper provides a generic tabular account of each type of technology when different design, installation, and maintenance aspects are considered. It should be noted that within these individual approaches there are many variants which can be used to best suit the design considerations at hand.

Some of the considerations given (Toderland,2010) include, engineering design constraints such as managing runoff, slope and crickets, roof loading, and wind uplift. It also provides some insight on installation methods as well as maintenance and repairs (FLL, 2002). It is concluded that rather than one being better than the other, it is better to think of them as different tools in the tool box to help solve our problems with urban runoff.

Overview

This comparison is based on general features of type of technology and not specific to any one technology as there are, in many cases, substantial differences within each technology. This comparison is not intended to demonstrate the one technology is better than the other, rather to demonstrate that each one has features which can be more suitable for a specific project application. In fact, in many case combinations of trays and built up system provide the best solution.

Table 1: A Comparative Overview of Technology Benefits

Category	Tray	Built Up
Stormwater Management	Trays can be designed to address specific stormwater management issues. As regulations increase to encompass LID techniques, green roofs as a component of site stormwater management will become more important.	Tend to be more passive in managing stormwater runoff. Water is stored within the retention layer and media only.
Retention	Trays can retain more water due to the physical barrier which prevents or restricts lateral flow thereby reducing annual runoff volume and irrigation demand. Trays can also store free water in wells or pockets.	Retain mostly gravitational water. Water retention on sloped roofs is reduced since there is no barrier to prevent lateral flow.
Detention	Can be designed to detain runoff to reduce peak flows as part of an LID component.	Reduces peak flow on more of a passive scale by freely draining at field capacity.
Evapotranspiration	More a function of the planting and soil media. However gas transfer from underneath and along the sides can increase water vapor transport however trays can restrict moisture transfer from one tray to the next.	More of a function of the planting and provides for a more uniform soil moisture distribution. In some cases lack of free water storage will decrease available water and increase the need for irrigation.

Category	Tray	Built Up
Slope	On sloped roofs prevent lateral flow to increase retained water. Often increased resistance to sliding or sloughing.	Sloped roofs will cause lateral flow thus reducing retained water and detained water. Also susceptibility to sloughing and sliding.
Cost (assuming a comparable media depth)	Cost is variable depending on method of installation and the depth of the system. Sometimes more expensive than an equivalent built up system and sometimes less.	Generally perceived as less expensive and generally true. In some cases other factors can make tray systems more cost competitive. Make sure when comparisons are being done that systems use an equal depth of media.
Design Flexibility	Less flexible on the design depth of the system and requires a hybrid approach with a built up systems to accommodate nooks, crannies and curves. Depending on planting methods, some trays allow for "artistic" shapes and patterns of the planting.	More variation in planting depth, albeit (sometimes leads to thin low cost profiles that can quickly fail) Easily cut to accommodate curves, nooks and crannies. Depending on planting methods allows for "artistic" shapes and patterns of the planting.
Fire	More of a function of the material from which the tray is made, the soil and plant type.	More of a function of the material from which the layers are made, the soil and plant type.
Weight	Can be lighter weight than the Built up alternative, depends on the type of tray. However the biggest influence on weight is the media, moisture content and plant density.	Can be lighter weight than the tray alternative, depends on the type of tray and built up profile. However the biggest influence on weight is the media, moisture content and plant density.
Roof Longevity	Depending on design offers a "hard interface" with the roof membrane to allow for free drainage and reduced moisture contact.	Depending on the design, may increase the presence of direct soil contact and prolonged or permanent moisture contact.
Roof Depressions	Can provide a "bridge" to elevate the soil media out of depressions which pond water and cause anaerobic conditions.	Can sag into depressions leaving the soil media in saturated conditions causing anaerobic conditions. Depends on the depth of the drainage layer.

Category	Tray	Built Up
Anchoring	Trays work well with metal edging to tie and anchor the tray system into the roof by a mechanical connection between the edging and the side of the tray.	Anchoring is not mechanical but rather the built up system is "tucked" underneath the edging overhang.
Point of Manufacturing	Molded trays can be manufactured most anywhere by shipping the mold only, to reduce shipping costs	Geotextiles generally manufactured in large single point facilities requiring long distance shipping.
Shipping	Stackable trays are highly space efficient and reduce shipping costs. Trays on pallets are easy to transport.	Rolls of higher porous material are lightweight but bulky and increase shipping costs. Rolls are sometimes difficult to handle.
Installation	There are many variations on installation methods which greatly impact cost. Least cost is to place empty trays, fill, and plant on the roof. Most costly is pre-grown trays. Sometimes the trays are directional and need care in correct orientation to the roof slope.	There are many variations on installation methods which greatly impact cost. Lower cost methods depend on shipping distances.
Pre-planted Tiles	Trays are set empty on the roof, partially filled with soil and "Tiles" are placed in the tray. Some top dressing is needed to cover tray edges.	Drainage layer, filter layer and retention layer are installed in a plywood fashion. The vegetated tiles are laid on the surface with or without a soil layer. Top dress to cover seams.
Cuttings	Trays are placed empty, filled with blown soil. Cuttings are applied and watered in. Inexpensive method but requires time to establish.	Drainage layer, filter layer and retention layer are installed in a plywood fashion. The soil layer is blown in. Cutting are applied and watered in. Inexpensive method but requires time to establish.
Plugs	Trays can be placed, blown with soil and then plugged, or prefilled, plugged and then placed. Trays can be placed in sequence to eliminate or minimize walking on the soil surfaces while transporting and placing plugs.	Drainage layer, filter layer and retention layer are installed in a plywood fashion. The soil layer is blown in. Plugs are applied and watered in. Inexpensive method but requires time to establish. Sometimes difficult due the intensive labor which can disturbs and compressed soil.

Category	Tray	Built Up
Maintenance	Walkable. Others may have issues with walking on the tray edge. Some trays have exposed edges which can cause burning of plants along the margins while others are overfilled and the tray edges are not exposed. Easy to dig out material from tray in the event of insect or weed infestation, dead plants, etc.	Walkable. Avoid damage to the retention and filer layer if soil digging is required to remove weed, insect infestation or dead plant removal.
Repairs	Individual trays can be removed and replaced without any change in the structural integrity of the system.	Cutting or the geotextiles is needed and interrupts the integrity of the built up system.

In some cases the best solution can be a hybrid design using a combination of tray and built up construction. Since advantages lie with each type of approach and each category needs to be considered with the design it becomes evident that at times there will be a conflict of which product to use. At that time the project designer needs to select the best overall option.

Conclusion

Table 1 is intended to be general guidelines and is not necessarily comprehensive for all project considerations. Within each design approach there are many differences that drive decision making. If any one conclusion is reached it should be that there is no one size fits all approach. Successful choices need to be based on the specific characteristics and design elements of the individual technology being evaluated. Many of the design elements can also be tested according to ASTM standard methods (ASTM, 2011).

Disclaimer

The authors wish to disclose they work for an organization that provides both built up and tray systems to the green roof market place. The statements above are opinions based on project experience and may not necessarily be shared by others. In addition, because of the various nature of different products, depending on the product, the statement may not apply.

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Estimating Annual Runoff Based on the NRCS Runoff Curve Number

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Abstract

The benefits of controlling stormwater runoff volume that results from land development activities have been well documented and are generally accepted by contemporary stormwater management practitioners. Although infiltration practices have been used for many years to mitigate the impacts associated with increased stormwater runoff, the benefits of more passive and non-structural approaches have only recently been recognized. Unfortunately, methods to quantify and assess those benefits have been limited, ranging from relatively simple empirical methods based on percentage of impervious cover to highly complex deterministic models which are beyond the needs of site-level analysis. In addition, the benefits from these so-called "green infrastructure" practices are generally associated with reductions in the annual runoff volume. Traditional stormwater management has relied on event-based methods to evaluate stormwater impacts and verify regulatory compliance. The Delaware Sediment & Stormwater Program has developed a methodology based on the Natural Resource Conservation Service's Runoff Curve Number (RCN) to estimate the annual runoff from developing lands and runoff reduction benefits associated with Green Technology Best Management Practices (GTBMPs) used to comply with State stormwater regulations. A spreadsheet compliance tool has also been developed based on the methodology.

Introduction

The benefits of controlling stormwater runoff volume that results from land development activities have been well documented and are generally accepted by contemporary stormwater management practitioners. Although infiltration practices have been used for many years to mitigate the impacts associated with increased stormwater runoff, the benefits of more passive and non-structural approaches have only recently been recognized. Unfortunately, methods to quantify and assess those benefits have been limited, ranging from relatively simple empirical methods based on percentage of impervious cover to highly complex deterministic models which are beyond the needs of site-level analysis. In addition, the benefits from these so-called "green infrastructure" practices are generally associated with reductions in the annual runoff volume. Traditional stormwater management has relied on event-based methods to evaluate stormwater impacts and verify regulatory compliance. The

Delaware Sediment & Stormwater Program has developed a methodology based on the Natural Resource Conservation Service's Runoff Curve Number (RCN) methodology to estimate the annual runoff from developing lands and runoff reduction benefits associated with Green Technology Best Management Practices (GTBMPs). This guidance document presents the scientific background behind, derivation of, and application of the methodology for compliance with the Delaware Sediment & Stormwater Regulations.

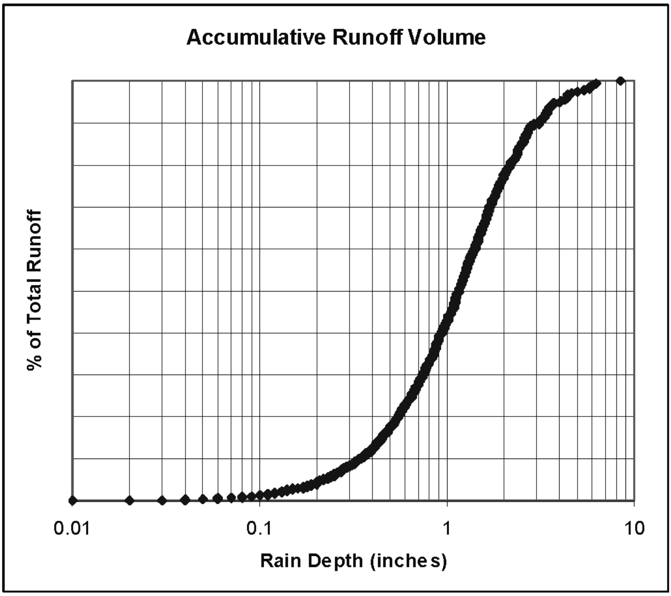
Background

It has been shown that the majority of the annual stormwater runoff is generated by small storm events accumulating over time. Dr. Robert Pitt of the University of Alabama is recognized in the scientific community as a national leader on the subject of small storm hydrology. Figure 1 illustrates his findings that rain events between 0.35" and 3" are responsible for about 80% of the total annual runoff volume based on data collected from BWI airport and modeled in his WinSLAMM model (Pitt 1998).

Although rainfall events less than 0.1" can account for up to 20% of the annual precipitation, as Figure 1 shows, they produce little if any runoff, which tends to skew the annual rainfall-runoff relationship. Based on Pitt's data, it was determined that the median runoff event was about 1.25 inches, which is approximately the 90th percentile rainfall event for the Delmarva region. That is, the 90th percentile rainfall event only accounts for about 50% of the annual runoff. This has important implications for stormwater management, particularly from a water quality and resource protection perspective. In order to manage the 90th percentile annual runoff volume, one would need to capture the runoff generated by the 99th percentile rainfall event.

Derivation of the Methodology

The research cited earlier by Pitt (2004) also included tabulated annual flow-weighted Rv values for various land uses and soils as calculated by his WinSLAMM model. Analysis of this data indicated that one could reasonably derive conjugate RCN values for the Rv values in the table. Several values were selected as representative of the typical RCN values used in Delaware for land development activities, ranging from ultra-low density residential site with sandy soils to commercial shopping center with clay soils. Figure 2 shows the Rv values selected for the analysis. Figure 3 shows the respective conjugate RCN values from the NRCS Technical Release 55.

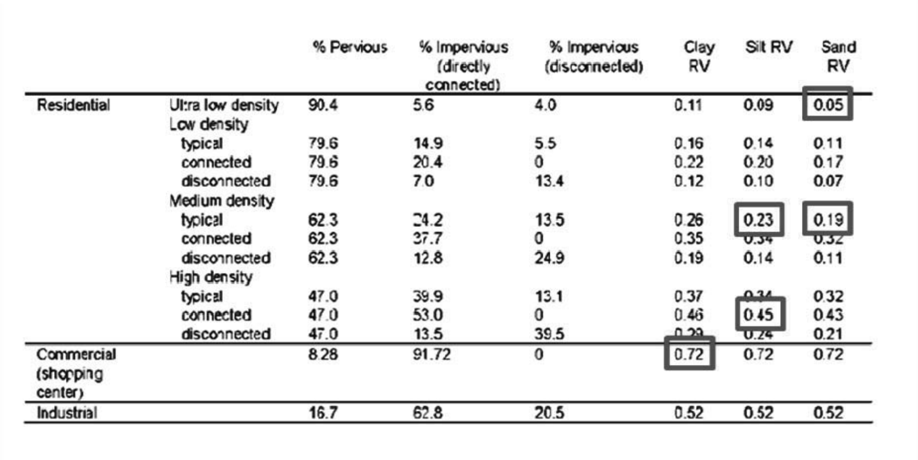


Plot showing accumulative runoff (100% full scale) against rain depth (Baltimore rains and typical medium density residential areas with silty soils).

Figure 1. (from Pitt & Vorhees, 2004)

Based on rainfall data from Wilmington, Dover and Georgetown, it was determined that the grand mean annual rainfall for Delaware was 43.85”. Using this annual rainfall amount, the selected WinSLAMM Rv values from Figure 2 were used to calculate the annual runoff for those land use/soil conditions. The Rv values were then paired with their conjugate RCN values, which were in turn plotted against the calculated annual runoff on log-log axes. Figure 4 is a graphic of this plot.

A regression analysis of Runoff Curve Number vs. annual runoff was then performed using the tools contained in Microsoft Excel™. Results from this analysis are shown in Figure 5.



		% Pervious	% Impervious (directly connected)	% Impervious (disconnected)	Clay RV	Silt RV	Sand RV
Residential	Ultra low density	90.4	5.6	4.0	0.11	0.09	0.05
	Low density						
	typical	79.6	14.9	5.5	0.16	0.14	0.11
	connected	79.6	20.4	0	0.22	0.20	0.17
	disconnected	79.6	7.0	13.4	0.12	0.10	0.07
	Medium density						
	typical	62.3	24.2	13.5	0.26	0.23	0.19
	connected	62.3	37.7	0	0.35	0.34	0.32
	disconnected	62.3	12.8	24.9	0.19	0.14	0.11
	High density						
	typical	47.0	39.9	13.1	0.37	0.34	0.32
	connected	47.0	53.0	0	0.46	0.45	0.43
	disconnected	47.0	13.5	39.5	0.29	0.24	0.21
Commercial (shopping center)		8.28	91.72	0	0.72	0.72	0.72
Industrial		16.7	62.8	20.5	0.52	0.52	0.52

Figure 2. (from Pitt & Vorhees, 2004)

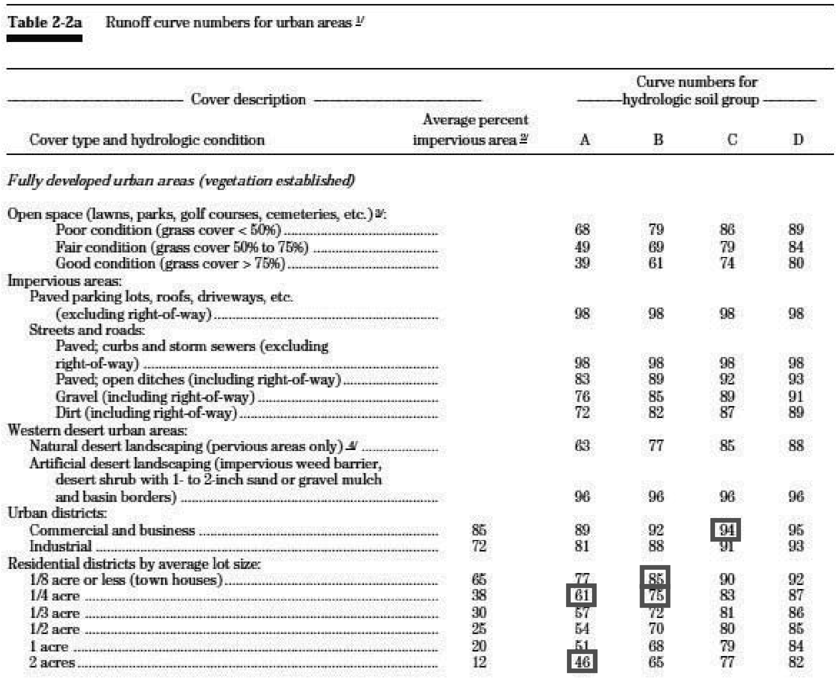


Table 2-2a Runoff curve numbers for urban areas [1]

Cover description: Cover type and hydrologic condition	Average percent impervious area [2]	Curve numbers for hydrologic soil group: A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.)[3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82

Figure 3. (from Table 2-2a, USDA-NRCS TR-55)

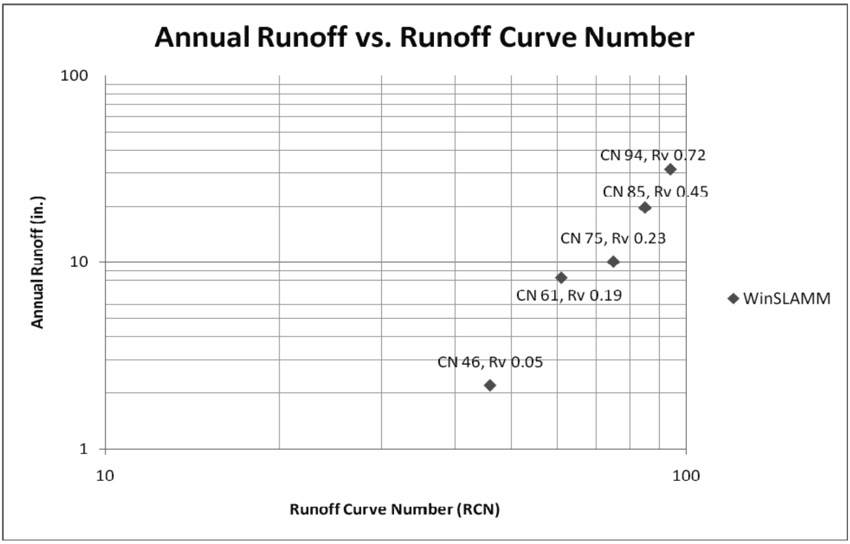


Figure 4. Log-Log Plot of Conjugate RCN/Rv Pairs vs. Annual Runoff

It was determined that the best fit for the data was a power function of the form $y = aX^b$, where a = 4.00034E-6 and b = 3.4902. The R^2 value for the regression was 0.9627. For regulatory purposes, it was decided that using a = 4.0E-6 and b = 3.5 would yield acceptable results that were within the uncertainty of the data, while simplifying the equations. Thus the equation to be used for compliance purposes under this methodology is:

$$\text{Annual Runoff (in.)} = 0.000004(\text{RCN})^{3.5} \qquad (\textit{Equation 1})$$

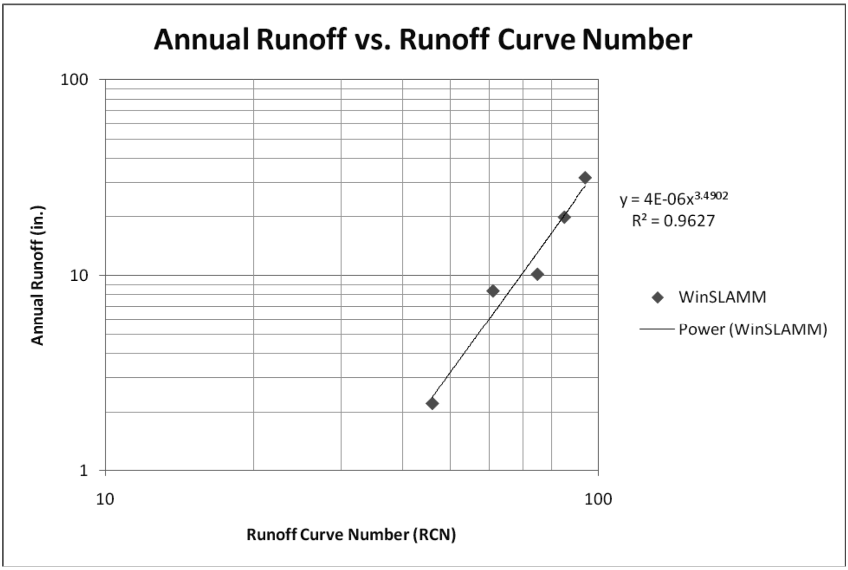


Figure 5. Regression Analysis of RCN vs. Annual Runoff

Application of the Methodology

If the NRCS Runoff Curve Number is known for a given drainage subarea, Equation 1 can be used to determine the annual runoff in watershed inches. This information is of limited use, however, without the benefits of runoff reduction practices being factored in. Although there is relatively little long-term data available on the ability of these practices to reduce runoff volume, the data that are available are typically based on the percentage of annual runoff reduction. The best source for this information currently available is the Chesapeake Stormwater Network's Technical Bulletin No. 4. While this document also contains a methodology for determining the appropriate "treatment volume" for these practices based on the 90th percentile annual rainfall, it was determined that a larger percentage of the annual runoff should be targeted for management under the Delaware Sediment & Stormwater Regulations. However, the information in this document related to runoff reduction is still deemed to be appropriate, albeit at some reduced level. Figure 6 is a table which summarizes the runoff reduction capabilities of various stormwater management practices as proposed to meet the requirements of the Delaware Sediment & Stormwater Regulations. The runoff reduction allowance for retention practices is based on their storage capacity and is independent of the soil type.

Practices that rely on passive infiltration and recharge have variable runoff reduction allowances based on the soil Hydrologic Soil Group (HSG).

The annual runoff reduction values from this table are used to determine the change in the annual runoff from a given drainage subarea. The adjusted Runoff Curve Number for that subarea can then be determined by rearranging Equation 1 and solving for RCN:

$$\text{RCN} = (\text{Reduced Annual Runoff}/0.000004)^{(1/3.5)} \qquad (\textit{Equation 2})$$

The steps required to perform the runoff reduction analysis can be summarized as follows:
Step 1: Determine annual runoff for subarea using Equation 1.
Step 2: Apply runoff reduction for selected practice based on values from Fig. 6.
Step 3: Adjust the Runoff Curve Number for the subarea using Equation 2.

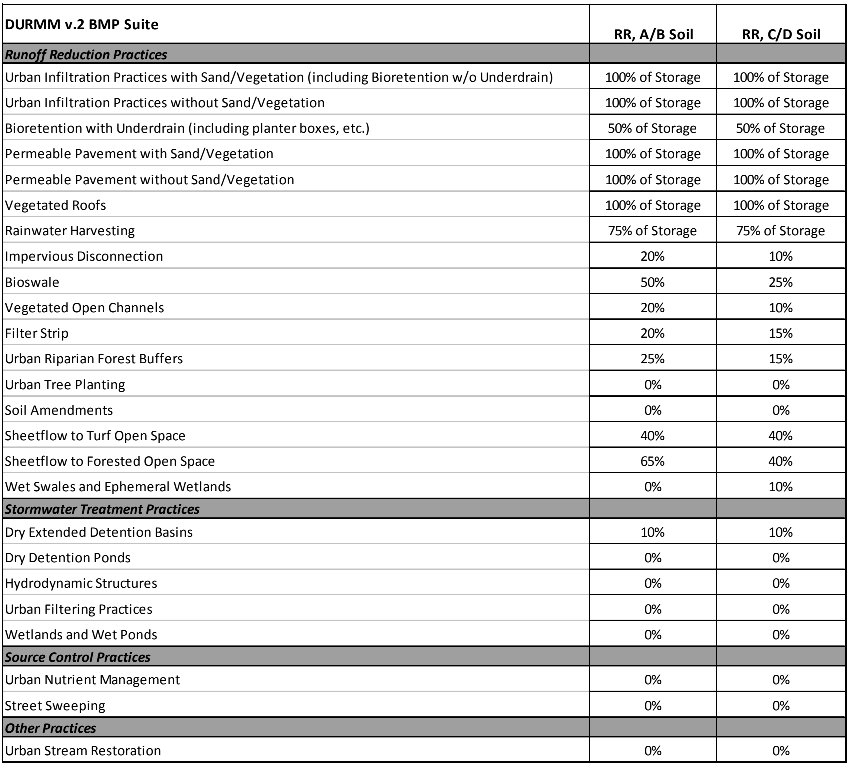
This process can be repeated for other practices in a “treatment train” within the subarea. The final adjusted Runoff Curve Number can then be used in traditional hydrologic programs to route more complex sites with multiple subareas.

Delaware Urban Runoff Management Model (DURMM)

The runoff reduction methodology lends itself well to the use of an automated spreadsheet solution. The DNREC Sediment & Stormwater Program has modified the DURMM spreadsheet program to include the runoff reduction procedures outlined in this guidance document. It is expected this updated version will become available upon adoption of the revised Regulations.

Runoff Reduction Methodology Caveats

- The methodology is proposed as an empirical compliance tool, not a physically-based solution of the rainfall-runoff relationship for developed sites.
- Under actual rainfall conditions, low magnitude events would be expected to be fully captured by the runoff reduction practices. However, as magnitude increases, the percentage of runoff volume captured decreases. Therefore, the runoff reduction calculated using this methodology for the Resource Protection Event should be viewed as an average value based on the annual rainfall distribution, not the reduction for a 1-YR storm event.
- The adjusted curve number (CN*) for infiltration and other retention practices having a storage component may be used for the Conveyance Event and the Flooding Event with modifications to the equations. The ability of runoff reduction practices to manage the runoff from these higher magnitude events is limited, though some nominal reduction allowance is warranted.



DURMM v.2 BMP Suite	**RR, A/B Soil**	**RR, C/D Soil**
Runoff Reduction Practices		
Urban Infiltration Practices with Sand/Vegetation (including Bioretention w/o Underdrain)	100% of Storage	100% of Storage
Urban Infiltration Practices without Sand/Vegetation	100% of Storage	100% of Storage
Bioretention with Underdrain (including planter boxes, etc.)	50% of Storage	50% of Storage
Permeable Pavement with Sand/Vegetation	100% of Storage	100% of Storage
Permeable Pavement without Sand/Vegetation	100% of Storage	100% of Storage
Vegetated Roofs	100% of Storage	100% of Storage
Rainwater Harvesting	75% of Storage	75% of Storage
Impervious Disconnection	20%	10%
Bioswale	50%	25%
Vegetated Open Channels	20%	10%
Filter Strip	20%	15%
Urban Riparian Forest Buffers	25%	15%
Urban Tree Planting	0%	0%
Soil Amendments	0%	0%
Sheetflow to Turf Open Space	40%	40%
Sheetflow to Forested Open Space	65%	40%
Wet Swales and Ephemeral Wetlands	0%	10%
Stormwater Treatment Practices		
Dry Extended Detention Basins	10%	10%
Dry Detention Ponds	0%	0%
Hydrodynamic Structures	0%	0%
Urban Filtering Practices	0%	0%
Wetlands and Wet Ponds	0%	0%
Source Control Practices		
Urban Nutrient Management	0%	0%
Street Sweeping	0%	0%
Other Practices		
Urban Stream Restoration	0%	0%

Figure 6. Runoff Reduction Allowances for Select Stormwater Management Practices

General Form of the Equation for Estimating Annual Runoff

The equations used in the methodology were developed specifically for use in Delaware. However, the DNREC Sediment & Stormwater Program has developed a general form of the equations that could be used in other locations assuming results can be verified under local conditions.

I. General equation for estimating annual runoff:

$$Annual\ Runoff\ (in.) = C_{Ra}(RCN)^{Exp}$$

Where:

C_{Ra} = annual runoff coefficient
RCN = NRCS runoff curve number
Exp = 3.5

II. Derivation of the annual runoff coefficient (C_{Ra}):

$$C_{Ra} = \frac{(P)(R_v)}{RCN_{R_v}{}^{3.5}}$$

Where:

P = annual precipitation (in.)
R_v = percent annual precipitation converted to runoff
RCN_{Rv} = conjugate NRCS runoff curve number at R_v

III. The analysis based on Pitt's results using WinSLAMM found that $R_v = 0.85$ at RCN = 98.

Substituting:

$$C_{Ra} = \frac{(P)(0.85)}{98^{3.5}}$$

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Development of Low Impact Development Design Guide

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Abstract

Low impact development (LID) design should fully consider local hydrological, climate, and soil characteristics. With the increasing popularity of LID and recognition of its contribution to sustainable development, many municipalities are developing or have developed LID design guide or manual. This paper discusses the processes, experiences and lessons learned from developing a LID-BMPs Design Guide for the City of Edmonton. This project had a series of workshops and roundtables to engage stakeholders to gain support and solicit feedbacks on the Design Guide. A modelling analysis was conducted to compare the LID-oriented neighborhood design with conventional neighborhood design regarding hydrologic performance, water quality improvement, life cycle cost, and benefits.

Introduction

Why LID is needed in Edmonton? The main driver of implementing low impact development (LID) best management practices (BMPs) in the City of Edmonton is the recognition of its importance to ensure sustainable urban growth and to support the City's environmental strategy. The City of Edmonton has experienced rapid population and urban growth over the past decade and sustained growth is expected to continue. The population of the City is 812,201 (2011). The total land area is 71,000 hectares (ha) with about 34,000 ha of urban footprint. Edmonton has both combined sewer systems and separate sewer system. The combined sewer system receives runoff from about 5,000 ha and the stormwater sewer system receives runoff from about 27,000 ha.

At the City of Edmonton, the drainage systems are regulated through Approval to Operate issued by Alberta Environment. The approval requires that the City to develop "a comprehensive Storm Water Quality Control (SWQC) Strategy and a plan for implementing this strategy" (Alberta Environment 2005). The SWQC

Strategy and an Action Plan was developed in 2008 to manage stormwater release and its impact to the North Saskatchewan River for protecting water quality in the river. This Strategy encourages LID to control runoff volume, attenuate peak flow, and improve stormwater quality (COE 2008). Later, developing and implementing a total loading plan became a new requirement under the Approval to Operate. The Total Loadings Plan (TLP) developed in 2009 established a framework for limiting annual loadings of contaminants from municipal operations including interconnections, combined sewer overflows, storm overflows, Gold bar wastewater treatment plant bypasses and final effluent to the North Saskatchewan River (COE 2009). Staged implementation of LID is a component of TLP. In 2011, LID was identified as an initiative to protect healthy ecosystem by the City's environmental strategic plan, *the way we green* (COE 2011a). The recently developed Combined Sewer Discharge strategy recommends using green infrastructure such as LID as an approach to further reduce CSOs. To support LID applications, the City saw the need of providing design guidelines and specifications that are suitable to Edmonton's climate and geotechnical context.

Consideration of Local Characteristics

Edmonton is the capital of Canadian province of Alberta. It is located on the North Saskatchewan River at a latitude and longitude of 53°34′0″N, 113°31′0″W, respectively. Edmonton has a relatively dry humid continental climate (Koppen climate classification *Dfb*) with extreme seasonal and cold temperatures. Soils within the Edmonton area are predominately silt loam and silty clay loam, and are frozen during winter. Local characteristics also include deep frost lines, repeating freeze-thaw cycles, short growing seasons, and significant snow melt water. Table 1 shows Edmonton climate characteristics.

Table 1. Edmonton Climate Characteristics (COE, 2011b)

Climate Parameter	Value
Average Annual Mean Temperature	3.9 °C
Average Daily Temperature, January	-11.7 °C
Average Daily Temperature, July	18 °C
Frost Free Days	100 - 200
Typical Frost Depth	2.3 m
Mean Monthly Snowfall	1.2 m
Average Annual Precipitation	477 mm

LID has been applied mostly in warm climate. The Edmonton local characteristics result in LID implementation challenges such as reduced biological processes, reduced soil infiltration, high concentrations of sediment and pollutants during spring melt, impact of salt and de-icing agents on vegetation health, high runoff volume during snowmelt, ice blocked inlets, and soil compaction if LID facility is used for snow storage. Developing LID design guide should fully consider these local characteristics.

The project to develop LID-BMPs Design Guide for Edmonton was commenced in February 2010 and completed in June 2011. This paper will discuss the processes, experiences and lessons learned from this project.

Development of LID-BMPs Design Guide

The project for developing LID design guide has three major tasks: develop a LID BMPs Design Guide (*Design Guide*); compare conventional versus LID neighborhood design through model simulation; and engage internal and external stakeholders to gain support and solicit feedback on the *Design Guide*.

LID-BMPs Design Guide

The project was initially planned to develop a LID BMPs Design Criteria composed of a set of Design Guidelines and Design Manuals for seven pre-selected LID features including bioretention, bioswale, green roof, permeable pavement, box planters, naturalized drainage ways, and rainwater harvesting for reuse. The intent of having Design Guidelines and Manuals was to provide design criteria to users that need different levels of details regarding LID design. The Design Guidelines was intended to promote high-level understanding of LID design.

The Design Manual was to provide specific design specifics, design parameters and tools, and operation and maintenance scheduling. The Guidelines and Manual were intended to be used together. The intended audience of the Manual is similar to the Guidelines with specific interests to engineers, landscape architects, approvers, and operation and maintenance personnel.

The Design Criteria Draft that composed of Design Guidelines and Design Manuals was circulated to stakeholders and discussed at round table sessions. The comments and modifications to the Draft include:

Design Criteria versus Design Guide: The first draft documents were titled as *Design Criteria*. Stakeholder feedback, suggested that the term *Criteria* implied that the document represented a *Standard* and that implementation of LID was mandatory. The document was more appropriately titled as a *Design Guide*, since the intended use of the document was to provide design guidance on the basic concepts and key design parameters appropriate for use in the Edmonton area.

Condense the Design Guidelines and Design Manuals: In terms of the presentation of the *Design Guide*, it was believed that the two parts should be integrated. Two separate documents invariably introduce some repetition of information. A single document was considered to be more efficient and practical

Demonstrative LID BMPs figures updates: Local LID project information is being collected to develop a database for sharing experiences and lessons learned. Demonstrative LID BMPs figures from local projects were added into the *Design Guide*.

Cost, benefit and limitations: A section of LID Benefits, Costs and Limitations were added into the *Design Guide*. Cost is perceived as a barrier for LID application and cost analysis is usually missed in most of LID design manual or guidelines. The limitations of LID should also be aware of during design stage. Thus, the limitations regarding when and where LID does not work are particularly discussed.

Cold climate considerations: Cold climate and its associated issues such as de-icing activities, snowmelt runoff, and freezing-thaw cycles were specifically discussed and mitigation methods were recommended. To support addressing cold climate challenges, the project team conducted an in-house literature study on LID applications in cold climates to demonstrate that LID is applicable in Edmonton.

Fully taking the comments from stakeholders, the LID-BMPs Design Guide was developed. It consists of 14 chapters, which covers the rational of developing LID, regulations and bylaws from three levels of government which might affect LID implementation, soil and climate characteristics of Edmonton, LID site planning methodology and process, and LID facility design and operation considerations.

Model Comparison Study

The model comparison study was intended to assess the benefits and drawbacks of constructing a LID-oriented residential development versus a conventional neighborhood. A series of models (e.g. EPA SWMM 5, SUSTAIN, MUSIC, LIFE, WBM, STORM) were compared and EPA SWMM 5 was selected. This is because the toolbox of EPA SWMM 5 has LID features designed specifically for LID modeling. It is also suitable for simulating rainfall-snowmelt runoff and pollutants wash-off, which address our cold climate needs and water quality improvement through LID. In particular, SWMM 5 module has been integrated into the City's drainage assessment model - MIKE URBAN.

This modeling study compared the hydrologic performance and life cycle cost of LID BMPs to conventional stormwater management concept. It also provided technical guidance for modeling LID in site planning and design. The modeling exercise supports the LID Site Planning and Design, Chapter 4.0 of the *Design Guide*. It demonstrates an approach and provides assistance to planning level LID neighborhood level design assessment.

In this modeling study, the LID-oriented neighborhood plan assumed the same housing and commercial density as conventional neighborhood plan but incorporated unique characteristics including connected green spaces and LID BMPs wherever applicable.

The modeling results demonstrated that LID BMP applications significantly reduce total seasonal runoff volumes, total duration of runoff events, total suspended solids and phosphorus loading to receiving water bodies, and marginally decrease detention storage. The pollutant loading reduction should be interpreted carefully because it highly depends on the efficiency of LID assigned in the SWMM 5 by the modeler. Performance monitoring data was not available at Edmonton when the models were developed. Thus, the efficiency of LID was estimated based on projects in similar climate conditions. Life cycle cost analysis showed that LID neighborhood plan was more costly. However, it should be noted that the analysis could not provide a full accounting of potential benefits because most of benefits could not be readily quantifiable, such as preservation of aquatic life, impact on costs of stream restoration, and enhancement of recreational use of water.

Stakeholder Engagement

The purpose of the stakeholder engagement plan is to educate stakeholders, garner feedback, and obtain buy-in to the Design Guide. Two information workshops were organized to advocate LID concepts during the development of the *Design Guide*. Two roundtable discussions were held to gain technical feedback to the *Design Guide* Draft.

The City internal stakeholders were Planning, Transportation, Park, and Drainage departments. The external stakeholders included Alberta Environment, developers (e.g. Urban Development Institute), engineering and landscape architects, NGOs (e.g. North Saskatchewan River Watershed Alliance, Alberta LID Partnership), and nearby municipalities.

Stakeholder Information Sessions. The stakeholder information sessions addressed important ideas, concepts, and provided awareness of constructing green infrastructure to stakeholders. The attendees were very engaged in the discussions. The attendees indicated several opportunities for LID implementation and raised concerns and questions, such as:

- The need for clarity of the roles and responsibilities of City departments
- How to use a “holistic approach” or an integrated approach for urban design
- A need for education and public awareness

Roundtable Discussions. Two sessions of roundtable discussions were held. The internal stakeholder session covered topics such as hydrologic design, site planning and facility design, local considerations and the seven LID BMPs in the *Design Guide*. The design guidelines and manuals are generally accepted by internal stakeholders. Some of the questions and comments include:

- How to measure the performance of LID BMPs? How to make sure they work?
- What are the operation and maintenance requirements and costs? The operation and maintenance is perceived as a challenge because of the variety of LID BMPs and their distributed small-scale sites?

The external roundtable session recommended four strategies to help to address challenges for LID implementation:

- Education and local experience
- Integrated/team approach to design and approvals
- Design and approval tools
- Pilot projects

The importance of ensuring that adequate tools and education are provided to the approval engineers was emphasized. Checklists and detailed schematic diagrams were recommended.

The feedback from stakeholders shows various concerns, requirements, and opportunities. Approvers, planners, and design engineers would like to have straightforward tools such as detailed LID BMP schematics, fact sheets, and checklist to help them plan, design, review, and approve LID projects. Operation engineers are interested in operation and maintenance (O & M) schedule requirements, O & M cost, liabilities and responsibilities, etc. Stakeholders recommend that demonstration and pilot projects should be used to showcase the benefits of LID and thus effectively promote LID.

Results

A LID BMPs Design Guide Edition 1.0 was published in January 2012 (http://www.edmonton.ca/environmental/wastewater_sewers/low-impact-development.aspx). It is a living document and the Edition 1.0 will be updated in three years. Further updates will depend on the progress of continuing LID studies, monitoring information, and engineering experiences in Edmonton. Feedbacks from stakeholder engagement have been either incorporated into the *Design Guide* or will be addressed in LID implementation study (November 2011 – June 2012). Specific requirements from approvers, planners, and engineers will be addressed through developing user-oriented fact sheets and checklists.

Lessons Learned

Lessons to learn from the project for developing LID-BMPs Design Guide include:

1. **Local considerations:** the design guide should carefully and effectively address local considerations due to the site-specific nature of LID BMPs.

Edmonton is within a cold climate zone. LID design guides developed by other municipalities should be used or referenced with care. The City of Edmonton's LID-BMPs Design Guide is tailored for its local climate and geographical conditions. The update of the *Design Guide* requires further research to understand the performance and cold climate adaptations of LID specifically in Edmonton. A good LID guide should be able to provide supports to the design of a sustainable development that well balance the social, environmental and economic requirements.

2. **Stakeholder engagement:** A stakeholder engagement strategy should be developed at the beginning of the project to allow stakeholders effectively provide inputs. Essential technical materials such as fact sheets and checklist should be provided for stakeholders to better understand LID, which is important to achieve stakeholder buy-in.
3. **Team building:** LID is initiated mainly to manage stormwater. LID comprises a set of site design approaches and small-scale stormwater management practices, which require a multi-disciplinary team such as water resource engineers, environmental engineers, biologist, soil engineers, and landscape architect etc.
4. **Education:** Stakeholder engagement revealed that there are still misunderstandings and concerns about LID BMPs. Public, government staff, and private industry should all be educated on the environmental, social and economic benefits along with the development and implementation of LID-BMPs Design Guide.

Demonstration projects: Demonstration projects are important to show the benefits of LID from all perspectives and help to resolve concerns particularly to local contexts. Although LID has been successfully applied in other localities, its viability under cold climate and tight soil conditions such as Edmonton needs to be further validated. Stakeholders could be engaged more effectively with the presence of successful LID demonstration projects

Next Steps

The stakeholder consultations provided valuable insights on LID implementation. Moving forward from the development of the *Design Guide*, the following work has been initiated:

- a research to resolve the design challenges addressing local climate and soil characteristics;
- develop LID monitoring protocols;
- develop checklists for approval, design, operation and maintenance;
- develop a training program on the *Design Guide*; and
- develop a LID implementation business process.

Acknowledgement

The LID-BMPs Design Guide was drafted in June 2011 by AMEC Earth & Environmental with assistance from Armin A. Preiksaitis & Associates Ltd. and Progressive Engineering Ltd. The Drainage Planning section of the City's Drainage Services Branch made further revisions to the Draft. The *Design Guide* development fully incorporated stakeholder inputs from information and technical roundtable sessions. The authors acknowledge the contributions and participation of key stakeholders including Parks, Community Services, Sustainable Development, Development Services, Buildings and Landscape Services and Transportation Services.

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Modeling to Quantify the Benefits of LID for CSO Reduction

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Abstract

This paper describes a hydrologic and hydraulic (H&H) modeling technique to quantify the benefits of stormwater Low Impact Development (LID) controls in terms of reduction of Combined Sewer Overflow (CSO) events, volume, and peak overflow rate. This paper can help sustainable developers estimate the number and size of LID controls needed to capture a certain amount of CSO discharge in a typical year. A Pennsylvania case study is presented to illustrate H&H modeling results.

Introduction

Sustainable or "green" stormwater infrastructure uses LID controls such as, rain gardens (bio-retention cells), green roofs, infiltration trenches, porous pavement, cisterns (rain barrels), and vegetative swales. It is designed to capture surface runoff close to its source at distributed (decentralized) locations using some combination of detention, infiltration, and evapotranspiration (Michael Baker Corporation, 2008; Shamsi 2011).

Recently, many U.S. cities have started to embrace the use of green infrastructure as a viable means of managing stormwater runoff from new and existing development. However, the benefit that this type of infrastructure plays in the reduction of CSOs is often overlooked.

There are several hypotheses about the LID benefits on CSO/SSO discharge including:

1. LID measures can extenuate runoff so peak flow rates are lowered, which should reduce the occurrence of rainfall induced CSO and SSO events.
2. LIDs can eliminate overflows resulting from the small and more frequent rainfall events. LIDs can capture runoff from 1-inch and smaller rainfall events.
3. LIDs can be designed to remove stormwater runoff from over 90% of storm events from entering the sewer collection system.

Unfortunately these statements have not been studied and researched thoroughly leading to reluctance and skepticism, especially in cold regions with clay soils. A study was conducted by the author in 2010-11 to validate the efficacy of these statements (Shamsi, 2011a). This study found that H&H modeling can be effectively used to verify and quantify the LID benefits and to design appropriate LID controls. It also indicated that the actual extent of LID benefits depends on the local conditions such as, climate, soils, and impervious land. Due to length constraints, this paper presents only selected findings of the study.

In September 2010, U.S. Environmental Protection Agency (EPA) released a new version (5.0.021) of Storm Water Management Model Version 5 (SWMM5) that offers Low Impact Development (LID) modeling capability for the first time. Five types of LIDs can be modeled: bio-retention cells (rain gardens), infiltration trenches, porous pavement, cisterns (rain barrels), and vegetative swales (U.S. EPA, 2010; CHI, 2011, Rossman, 2010):

- Bio-retention Cells are depressions that contain vegetation grown in an engineered soil mixture placed above a gravel drainage bed. They provide storage, infiltration and evaporation of both direct rainfall and runoff captured from surrounding areas. Rain gardens, street planters, and green roofs (Chen and Li, 2010) are all variations of bio-retention cells.
- Infiltration Trenches are narrow ditches filled with gravel that intercept runoff from upslope impervious areas. They provide storage volume and additional time for captured runoff to infiltrate the native soil below.
- Porous Pavement systems are excavated areas filled with gravel and paved over with a porous concrete or asphalt mix. Normally all rainfall will immediately pass through the pavement into the gravel storage layer below it where it can infiltrate at natural rates into the site's native soil.
- Rain Barrels (or Cisterns) are containers that collect roof runoff during storm events and can either release or re-use the rainwater during dry periods.
- Vegetative Swales are channels or depressed areas with sloping sides covered with grass and other vegetation. They slow down the conveyance of collected runoff and allow it more time to infiltrate the native soil beneath it.

Although some LID controls can also provide significant pollutant reduction benefits, at this time SWMM5 only models their hydrologic performance. During a simulation SWMM5 performs a moisture balance that keeps track of how much water moves between and is stored within each LID layer.

Case Study

To demonstrate the H&H modeling application for designing LID solutions, a SWMM5 continuous simulation model was created for a 100-acre area in southwestern Pennsylvania shown in Figure 1.

Figure 1. Study Area Map

The case study area is part of a larger 3,000 acre (1,214 hectare) combined and sanitary sewer service area. The service area model was calibrated and verified for the baseline conditions, i.e., before adding any LIDs. Observed data for model calibration and verification was collected from 25 automatic flow monitors (with pressure and velocity sensors) and 3 rain gauges installed throughout the service are for 6 months from March to September 2009.

The pre-LID model had the following parameters: annual rainfall total = 32.4 in (typical year 2005), drainage area = 100-acre, land percent impervious = 50%.

The pre-LID model provided the following CSO results: number of CSO events = 45, Peak CSO flow rate = 25.73 MGD, CSO overflow volume = 14.93 MG.

The initial post-LID model included 10 rain gardens (0.1 units/acre) with the following properties: Area = 500 ft^2, Vegetative cover: 90%, Soil layer = 18 in, Soil porosity = 0.5, Soil conductivity = 0.5 in/hr, Gravel layer = 12 in, Gravel void ratio = 0.83, Gravel conductivity = 10 in/hr.

The initial post-LID model with 10 rain gardens provided the following CSO results: Number of CSO events = 44, Peak CSO flow rate = 24.15 MGD, CSO overflow volume = 14.41 MG, Percent capture of CSO volume = 3.5%.

Obviously, 0.1 units/acre reduced the CSO events marginally with only a 3.5% annual CSO volume capture. To achieve a target 85% capture, number of rain gardens was increased incrementally. Results are shown in Figure 2.

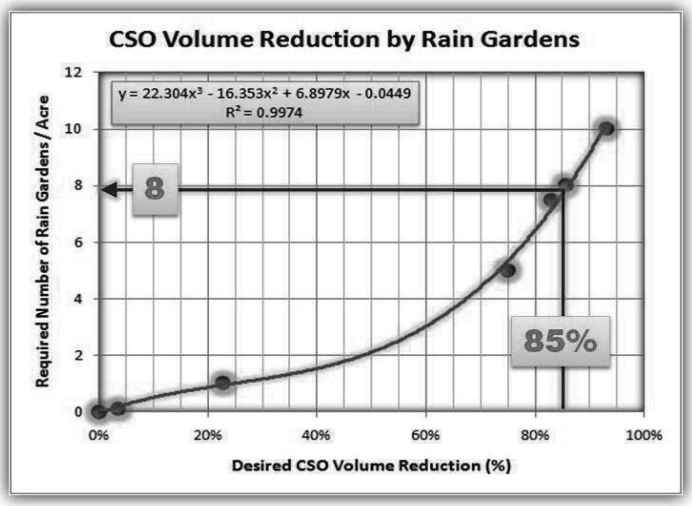

Figure. 2. Percent Capture vs. Number of Rain Gardens

The optimal number of rain gardens that met the 85% capture target was found to be 800 or 8 units/acre. The final post-LID model provided the following CSO results: Number of CSO events = 16, Peak CSO flow rate = 13.01 MGD, CSO overflow volume = 2.16 MG, Percent capture of CSO volume = 85.5%.

Effect of Soil Type

The existing model was based on the study area soil type of silt loam (hydrologic soil group B/C) with saturated hydraulic conductivity (K) of 0.26 in/hr. Next, the effect of soil types was studied by rerunning the model with different Green-Ampt input parameters to reflect different types of native soils. The results are presented as a hydraulic conductivity sensitivity plot in Figure 3. It can be seen that for sandy loam soils (hydrologic soil group B, K = 0.43 in/hr), there is no significant effect on the CSO peak and volume for the typical year. For loam soils (hydrologic soil group C, K = 0.13 in/hr), there was a 10% increase in CSO peak and volume. For clay soils (hydrologic soil group D, K = 0.01 in/hr), there was a 25% increase in CSO peak and volume.

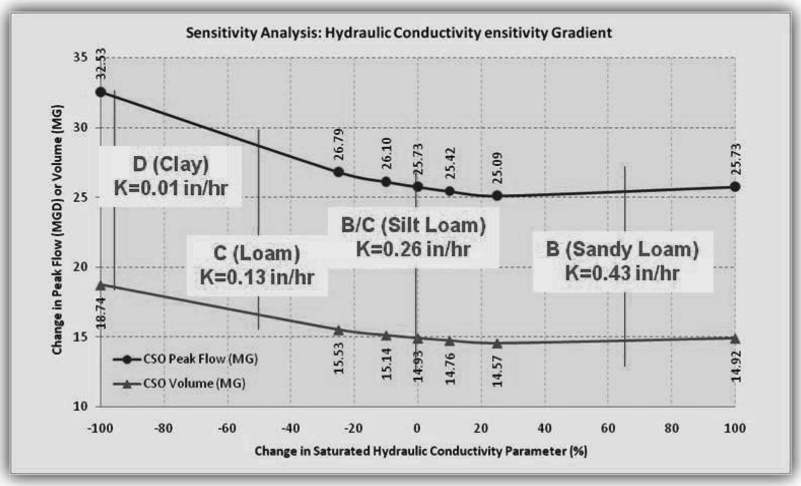

Figure 3. Soil Type Sensitivity Plot

Conclusions

From the case study results presented in this paper it can be concluded that rain gardens can be used to substantially reduce sewer overflows. However, the required number of rain gardens for high CSO volume reduction may be large in certain types of climates and soils. SWMM5 continuous simulation method can be used to determine the optimal number of rain gardens for various overflow control targets.

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A Saturated Seepage Flow Model for Low Impact Development Devices

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Abstract

A numerical model has been developed to define the saturated seepage zone under Low Impact Development (LID) devices, such as an infiltration trench, rain garden, bioretention pond, and underground infiltration chamber. The numerical model is established on Microsoft Excel spreadsheets and executed with computer programs as embedded functions in the spreadsheets. The programs were written using Visual Basic. The model can show the graphical results of the seepage zone. The Boundary Element method is applied in the model. To determine the free surface of the saturated seepage zone, a few numerical iterations will be required in the model. The seepage flow rate in steady state can be computed with this model.

The Given Boundary of Saturated Seepage Flow

On the first sheet (Excel tab labeled as “Input”) of the model established using Microsoft Excel 2003 (Microsoft Corporation), users need to assign XY coordinates (see Figure 1) for each point on the vertical section view of the LID devices. As shown below, the points A, B, C, and D are assigned by users. Those points and their connection lines are the given boundary of the saturated seepage flow. The vertical line connecting A and B coincides with the centerline of the device section. The length between A and B represents the distance between the device bottom and the water table. The horizontal line between B and C represents one half of the device bottom. The line connecting C and D is the side wall of the device. Point E will be automatically set by the computational model as an assumed end point of the unknown phreatic line, which will be solved by the model later. The line connecting A and E is the water table.

On the Microsoft Excel Spreadsheet (see Table 1) users enter the X and Y coordinates of the above points into the blue shaded area, except point E. The seepage flow exit at D is a contact point of the storage water surface at the side wall.

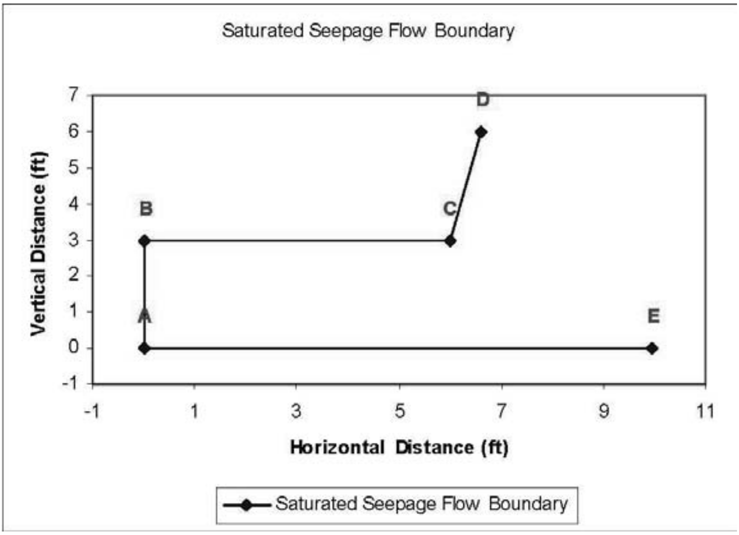
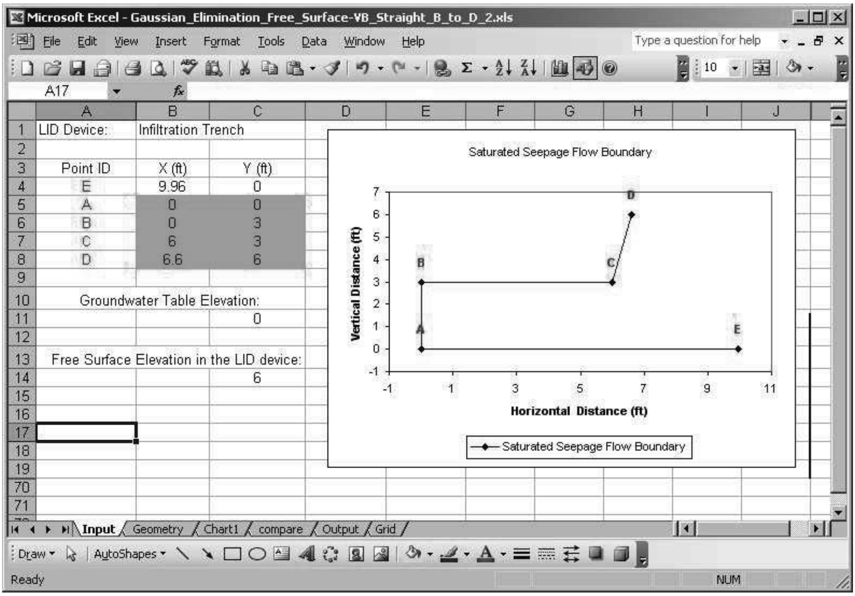


Figure 1. The given boundary of the saturated seepage flow.

Table 1. Input data for modeling seepage area.

LID Device:	Infiltration Trench	
Point ID	X (ft)	Y (ft)
E	9.96	0
A	0	0
B	0	3
C	6	3
D	6.6	6
Groundwater Table Elevation:		
		0
Free Surface Elevation in the LID device:		
		6

The horizontal coordinate of the point E on the water table is not known at the time when users enter XY coordinates (Golberg, 1995), but the model can set the point E as a temporary trial location. However, the horizontal location of the point E will be solved later by the model with numerical iterations. A general view of the first sheet is shown in Figure 2.



Microsoft Excel - Gaussian_Elimination_Free_Surface-VB_Straight_B_to_D_2.xls

LID Device: Infiltration Trench

Point ID	X (ft)	Y (ft)
E	9.96	0
A	0	0
B	0	3
C	6	3
D	6.6	6

Groundwater Table Elevation:
0

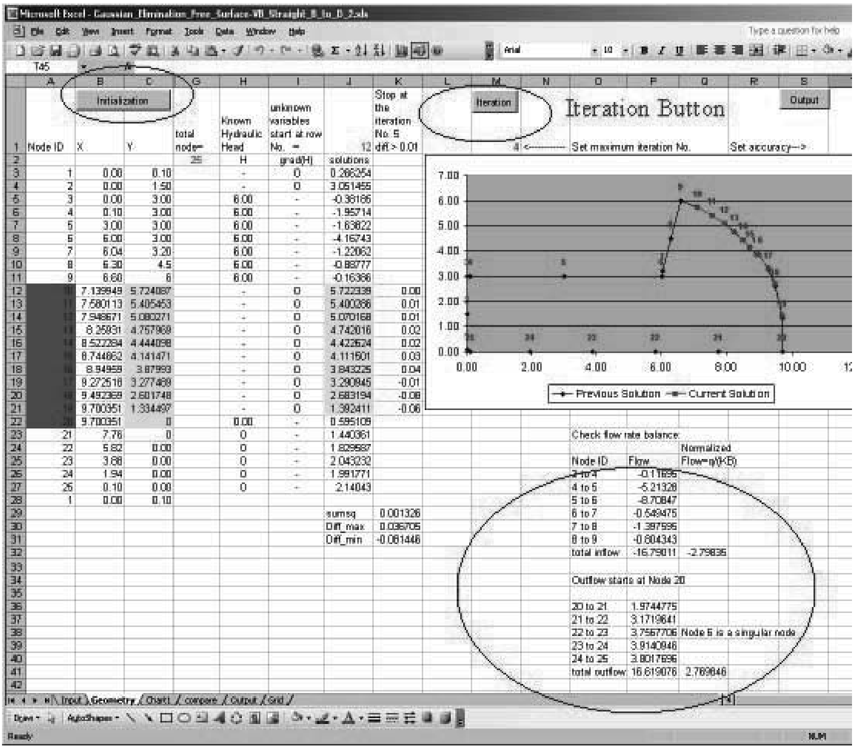
Free Surface Elevation in the LID device:
6

Figure 2. General view of input data sheet.

The unknown seepage free surface profile is between points D and E. The model will solve the unknown free surface profile and seepage flow rate flowing out of the device based on potential flow theory and Darcy's law (Freeze and Cherry, 1972). The graphical results of the free surface of seepage flow are shown on the second Excel sheet (tab labeled as "Geometry") during the numerical iterations with the Boundary Element Method (Beer and Watson, 1992). After the modeling is completed by a few numerical iterations, a final seepage profile is shown on the third Excel sheet (tab labeled as "Chart1") of the model.

Executing the Model to Determine the Free Surface Profile

After users have correctly established input data on the first sheet, the next step is to execute the model and determine the free surface profile of the saturated seepage flow. On the second Excel sheet of the model, users need to click the "Initialization" button (circled in red on the left upper corner of Figure 3) to initiate the modeling.



	A	B	C	G	H	I	J	K
1	Node ID	X	Y	total node=	Known Hydraulic Head	unknown variables start at row No. =	12	Stop at the iteration No. 5 diff > 0.01
2				25	H	grad(H)	solutions	
3	1	0.00	0.10		-	0	0.286254	
4	2	0.00	1.50		-	0	3.051455	
5	3	0.00	3.00		6.00	-	-0.38186	
6	4	0.10	3.00		6.00	-	-1.95714	
7	5	3.00	3.00		6.00	-	-1.63822	
8	6	6.00	3.00		6.00	-	-4.16743	
9	7	6.04	3.20		6.00	-	-1.22062	
10	8	6.30	4.5		6.00	-	-0.88777	
11	9	6.60	6		6.00	-	-0.16366	
12	10	7.139949	5.724087		-	0	5.722339	0.00
13	11	7.580113	5.405453		-	0	5.400266	0.01
14	12	7.948671	5.080271		-	0	5.070168	0.01
15	13	8.25831	4.757969		-	0	4.742016	0.02
16	14	8.522284	4.444098		-	0	4.422624	0.02
17	15	8.744862	4.141471		-	0	4.111501	0.03
18	16	8.94959	3.87993		-	0	3.843225	0.04
19	17	9.272516	3.277469		-	0	3.290845	-0.01
20	18	9.492369	2.601748		-	0	2.683194	-0.08
21	19	9.700351	1.334497		-	0	1.392411	-0.06
22	20	9.700351	0		0.00	-	0.595109	
23	21	7.76	0		0	-	1.440361	
24	22	5.82	0.00		0	-	1.829687	
25	23	3.88	0.00		0	-	2.043232	
26	24	1.94	0.00		0	-	1.991771	
27	25	0.10	0.00		0	-	2.14043	
28	1	0.00	0.10					
29							sumsq	0.001326
30							Diff_max	0.036705
31							Diff_min	-0.081446

Iteration Button

4 <———— Set maximum iteration No.

Set accuracy—>

Check flow rate balance:

Node ID	Flow	Normalized Flow=q/(KB)
3 to 4	-0.11695	
4 to 5	-5.21328	
5 to 6	-8.70847	
6 to 7	-0.549475	
7 to 8	-1.397595	
8 to 9	-0.804343	
total inflow	-16.79011	-2.79835

Outflow starts at Node 20

20 to 21	1.9744775	
21 to 22	3.1719641	
22 to 23	3.7567706	Node 6 is a singular node
23 to 24	3.9140946	
24 to 25	3.8017696	
total outflow	16.619076	2.769846

Figure 3. General view of the second sheet of the model.

After the modeling is initiated, a straight blue line that represents the preliminary free surface profile, starting from Point 9 through point 20 (see Figure 4), will be shown with the given boundary on the same sheet. On the second Excel sheet (tab labeled as "Geometry"), the identification of each modeling point and its X and Y coordinates are shown in the first three columns. The X and Y values within the yellow shaded area can be adjusted manually by users during the numerical iterations done by the model. The blue shaded area presents the solutions provided by the model. Those solutions in the blue shaded area are the elevations (Y coordinates) of the free surface profile. In the same column of solutions, the solved hydraulic gradients of their corresponding points are shown outside the blue shaded area. The data in the eighth column corresponds with the differences between current and previous hydraulic heads of the free surface profile.

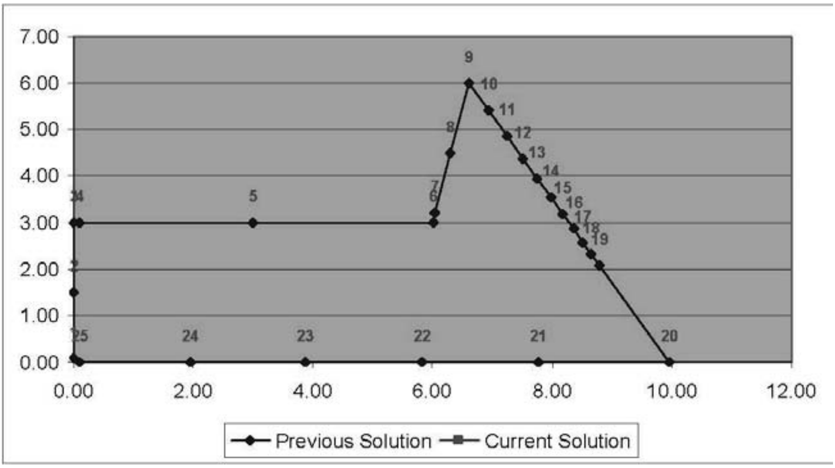


Figure 4. Preliminary free surface profile with given boundary.

After clicking the "Iteration" button, the blue straight line will be revised by the model. Users can define the maximum iterations and the accuracy of hydraulic head at the free surface. The iterations will continue until the required accuracy is reached and the seepage flow rates are balanced between the device bottom and the water table. The seepage flow rates for inflow at the device bottom and outflow at the water table are shown near the lower right corner of the second Excel sheet (tab labeled as "Geometry") of the model.

Since point 19, adjacent to point E (point 20), is sensitive to the numerical solution of the seepage surface, users need to manually adjust the Y coordinate of that point when the profile is not visually viewed as a smooth curve. In general, users adjust the hydraulic heads, which are Y coordinates in the yellow zone of the second Excel sheet of the model, along the surface profile to improve the accuracy and the seepage rate balance after several iterations. A final solution, as an example, is shown on Figure 5.

If the graphical solution is erratic or unexpected numerical divergence occurs after clicking the "Iteration" button, users can stop the execution and then click the "initialization" button to restart the modeling.

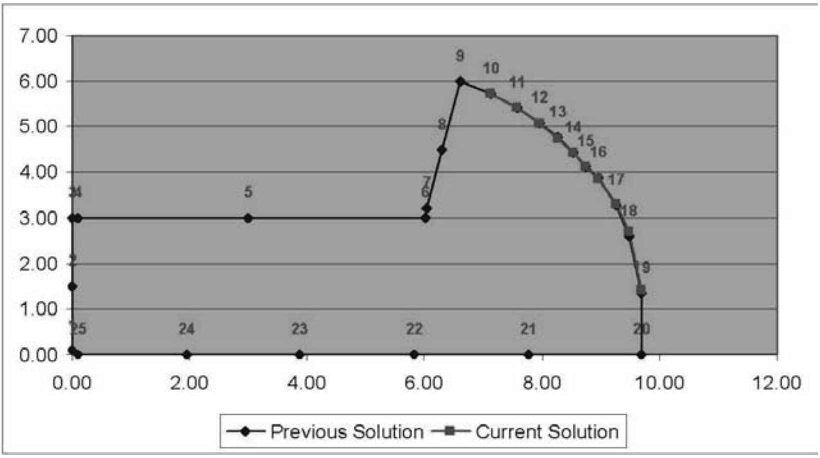


Figure 5. Final solution of the free surface profile.

Conclusions

The blue line is the current solution overlaid partially by the red profile, which is the line of the previous solution, as shown in Figure 5. The profile provides designers a way to lay out an appropriate location (Barraud, Gautier, Bardin, and Riou 1999) for some adjacent structures to avoid seepage flow encroachment and earth slope failure.

The computed seepage flow rate by the model can assist designers to evaluate the storage detention time for an installed LID device.

In the model there are numerically singular points, such as point 6 and point 20. Those singularities can produce numerical errors in the above modeling case. Therefore, in the drainage design for LID devices the effect of the singularity on the computational error may need to be studied in the future to assure the error caused by the singularity of those points may not be critical in the design.

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Open Canopy in Urban Streams Induces Seasonal Variation in Transient Storage

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Abstract

Transient storage plays an important role in pollutant assimilation in urban streams by allowing additional time for physical, chemical and biological transformation and uptake. While riparian forests provide many ecological benefits, few studies have examined the impact of riparian vegetation on the seasonal variability of transient storage. We investigated transient storage in four reaches of Dead Run, Baltimore, Maryland and four reaches of Valley Creek, Chester County, Pennsylvania. All reaches drained urban areas with impervious surface cover ranging from approximately 13%-28% in Valley Creek to 40%-60% in Dead Run. In each watershed, two reaches had a riparian forest which provided complete canopy cover over the stream channel and two reaches had an open canopy over at least 23% of the reach. Transient storage in both watersheds varied widely, accounting for as much as 25% of median travel time in Dead Run and tributary reaches of Valley Creek and as little as 0.01% of median travel time in the Valley Creek main stem reaches. In closed canopy reaches, there was no statistically significant seasonal trend in the median travel time attributable to transient storage (F_{med}). However, in open canopy reaches, the time of year explained approximately 59% of the variation in F_{med}, increasing from spring to summer. We conclude that the absence of canopy cover will induce a seasonal pattern in which transient storage is minimized in spring and maximized during the summer and early autumn growing season.

Introduction

Transient storage zones are areas where water and solutes are temporarily delayed in their downstream transport. Transient storage zones can be found within the surface water (e.g., within side pools, behind debris dams, within stands of aquatic vegetation) and in the subsurface or hyporheic zone (e.g., beneath riffles, through side and center bars and within stream banks).

Transient storage plays an important role in delaying downstream transport of contaminants due to both hydrologic retention (within surface and/or subsurface dead zones) and physical sorption to bed sediments (Bencala et al. 1983; Bencala et al. 1984; Bencala 1984).

Researchers have also shown that transient storage plays an important role in lotic ecosystem function. Both community respiration and community metabolism are directly connected to transient storage and, in particular, hyporheic exchange. As hyporheic exchange increases, both community respiration and community metabolism increase (Mulholland et al. 1997), with the hyporheic zone accounting for up to 93% of community respiration in some streams (Fellows et al. 2001). Not surprisingly, then, the hyporheic zone, and more generally transient storage, is an important driver of nutrient transformation and removal. Hyporheic exchange plays a significant role in nitrification of ammonium-rich groundwater (Triska et al. 1993a; Triska et al. 1993b) as well as denitrification of nitrate-rich surface waters (Morrice et al. 1997; Valett et al. 1997). Surface storage zones may also play a key role in denitrification since these zones provide greater contact time between nitrate-rich surface water and denitrification sites located within near-surface bed sediments (Hill et al. 1998). Phosphorus uptake is also at least partly controlled by transient storage characteristics (Mulholland et al. 1997; Ryan et al. 2007). Protecting and maintaining the transient storage zone (in both the surface waters and in the subsurface hyporheic zone) may help improve nutrient removal efficiencies since urbanizing streams are often less efficient at nutrient removal compared to non-urban streams (Paul and Meyer 2001; Ryan et al. 2007).

Because transient storage plays such an important role in the functioning of streams, it is also important to understand the factors that control transient storage. Heterogeneity of bed sediment permeability or hydraulic conductivity, stream bed gradient, and bed sediment depth have long been recognized as primary drivers of surface-subsurface (hyporheic) exchange (Vaux 1962).

While the relationship between grain size and hydraulic conductivity has also been well established (Hazen 1892), it has recently been shown that even small quantities of fine grain sediment can clog the upper bed sediment and effectively cut off surface-subsurface exchange (Packman and MacKay 2003; Ryan and Packman 2006). However, the influence of hydraulic conductivity heterogeneity can be masked by the influence of groundwater gradient and sinuosity (Ryan and Boufadel 2006; Ryan and Boufadel 2007) as well as the influence of bed forms (Cardenas and Zlotnik 2003; Cardenas et al. 2004).

Bed forms induce pressure head variation which will ‘push’ surface water into the hyporheic zone on the upstream side and ‘pull’ water into the surface zone on the downstream side (Thibodeaux and Boyle 1987). Debris dams are expected to have a similar impact on pressure head and thus induce hyporheic exchange, as well as provide transient storage in the surface water behind the dams (Ensign and Doyle 2005; Hart et al. 1999).

While many drivers of heterogeneity do not necessarily vary with season (e.g. sediment grain size, bed forms and debris dams), other drivers of heterogeneity are seasonally variable. For example, periphyton and aquatic vegetation can increase roughness in the channel, resulting in reduced velocities (Nikora et al. 1997; Schulz et al. 2003) which will increase residence time and surface storage during the growing season. In addition, these features may increase pressure head variation which is a function of the square of the stream velocity (Elliott and Brooks 1997a; Elliott and Brooks 1997b). As the stream water encounters the upstream side of vegetation, the increase in pressure will drive surface water into the subsurface, leading to an increase in hyporheic exchange (Hendricks and White 1988; Thibodeaux and Boyle 1987) during the growing season.

Land development often results in wider stream channels (Arnold et al. 1982; Hammer 1972), which may decrease canopy cover. Since periphyton and aquatic vegetation are most prevalent in open-canopy stream reaches (Sabater et al. 2000), we hypothesize that seasonal variation in transient storage in urban streams will also be most prevalent in reaches with open canopy.

Site Locations

To test the hypothesis, we analyzed data from conservative solute injection studies conducted in Dead Run, Baltimore County, Maryland and in the Valley Creek, Chester County, Pennsylvania watershed.

Dead Run drains a 20.4 km^2 watershed within the Piedmont physiographic region of Maryland underlain by igneous and metamorphic bedrock. In 2004, impervious surfaces covered approximately 40% of the Dead Run watershed (Ryan et al. 2010). In 2000, 56.1% of the watershed was used for residential purposes and 39.3% was used for commercial and industrial purposes (Beighley and Moglen 2003). Tracer tests were conducted in four reaches of Dead Run in 2007 and 2008 (Figure 1). Two reaches (D1 and D4) had complete canopy cover (Table 1) and two reaches (D2 and D3) had varying amounts of open canopy (Table 1).

Valley Creek drains a 60 km^2 watershed located within the Piedmont physiographic region of southeast Pennsylvania. The main stem of the creek is located in a dolomite and limestone formation while the northern ridge of the watershed consists of quartzite and the southern ridge consists of phyllite (Bascom and Stose 1938). In 2001, the single largest land use category was residential (35%) followed by commercial (17%). Approximately 16% of the watershed was covered with impervious surfaces (Emerson 2003). Tracer studies were conducted in four reaches within the Valley Creek watershed (Figure 2). Two reaches (V1 and V3) had a forested riparian corridor that provided complete canopy cover during the summer and early autumn seasons (Table 1). Two reaches (V2 and V3) had a more varied riparian corridor which left much of the reach length with a completely open canopy (Table 1).

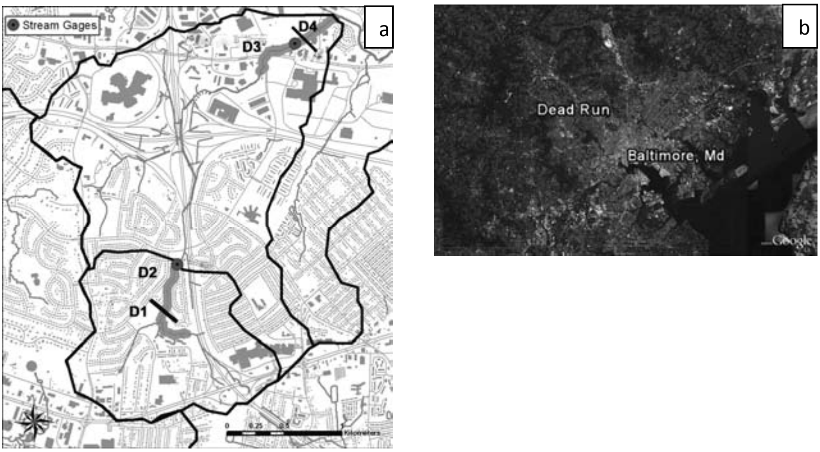

Figure 1. Dead Run watershed. In the left panel, the stream channel is shown in blue and the locations of tracer injection experiments are highlighted. Impervious cover is shown in grey. The right panel shows the location of Dead Run watershed relative to Baltimore, Maryland.

Table 1. Characteristics for Dead Run (D) and Valley Creek (V).

Reach	**Length** (m)	**Average Slope**	**Flow Range** (L/s)	**Impervious Cover** (%)	**Open Canopy** (%)
D1	455	0.015	0.82 – 2.7	43	0
D2	455	0.007	1.4 – 5.2	41	100
D3	425	0.003	1.6 -24.7	47	23
D4	545	0.003	2.7 – 29.8	48	0
V1	1660	0.004	185 - 493	15	0
V2	3240	0.003	233 - 640	13	57
V3	178	0.025	7.0 – 40.3	28	79
V4	238	0.051	1.7 – 8.9	27	0

NOTE: Flow range indicates the highest and lowest flow measured at the head of each reach for the various tracer injection experiments. Percent impervious cover is for the area draining to the downstream station of each reach. Open canopy is the percent of reach length with no canopy cover.

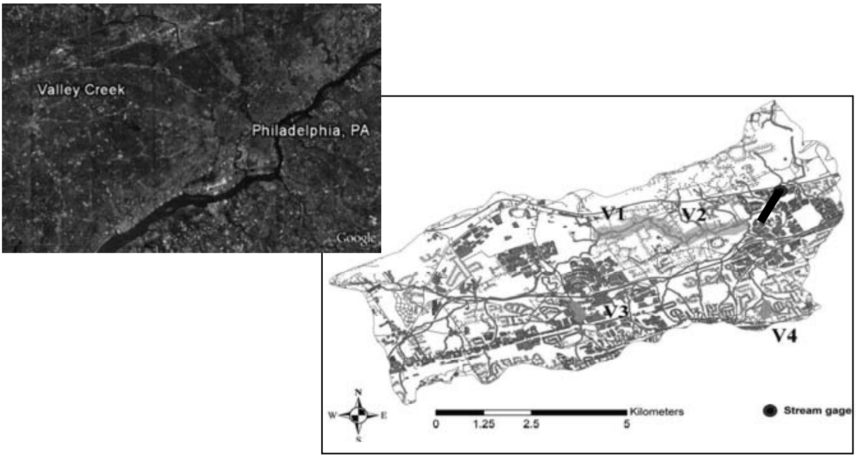

Figure 2. Valley Creek watershed. In the right panel, the stream channel is shown in blue and the locations of tracer injection experiments are highlighted. Impervious cover is shown in grey. The leftt panel shows the location of Valley Creek relative to Philadelphia, Pennsylvania.

Methods

Details regarding the Dead Run tracer tests are described in Ryan et al. (2010). The Valley Creek tracer tests are described in Ryan et al. (2004), Ryan and Packman (2006) and Ryan et al. (2007). In brief, for each test we injected a sodium bromide (NaBr) solution using a peristaltic pump for periods ranging from 1 hour to 24 hours. Samples were collected at downstream stations at intervals ranging from 3 minutes to 1 hour. Shorter sampling intervals were used during the time when the BTC was estimated to be rising and falling. Longer intervals were used during the time when the BTC was expected to be at a plateau concentration and during the expected late tailing period of the BTC. All samples were kept on ice or refrigerated until analysis using a Dionex Ion Chromatograph. Estimates of the transient storage area (A_s) and exchange rate (□) were determined by analyzing the breakthrough curves (BTC) using OTIS-P (Runkel 1998). The BTC were also used to estimate reach average velocity (time to reach 50% of the BTC plateau concentration divided by reach length). Stream flow rate was determined using either the velocity-gaging method (Carter and Davidian 1968) or, in the case of very low flows in some locations in Dead Run, volumetrically using a bucket and stopwatch. In addition, stream flow at downstream stations was estimated based on dilution using Eq. 1.

$$Q_{down} = Q_{up} \frac{C_{up}}{C_{down}} \tag{1}$$

Where:
Q_{down} is the dilution-estimated flowrate at the downstream station (L s^{-1}),
Q_{up} is the velocity- or volumetrically-estimated flowrate measured at the upstream station (L s^{-1}),
C_{down} is the tracer plateau concentration measured at the downstream station (mg L^{-1}), and
C_{up} is the tracer plateau concentration measured at the upstream station (mg L^{-1}).

The importance of transient storage in each reach was determined based on the fraction of median travel time attributable to transient storage, F_{med} (Runkel 2002), using Eq. 2.

$$F_{med} \cong \left(1 - e^{-L\left(\alpha/V\right)}\right)\frac{A_s}{A + A_s} \tag{2}$$

Where;
L is the reach length (m),
α is the transient storage exchange rate coefficient (s^{-1}),
V is the reach-average stream velocity (m s^{-1}),
A_s is the cross sectional area of the transient storage zone (m^2), and
A is the cross sectional area of the main channel (m^2).

Residence time in a reach is a function of reach length and so it is important to compare reaches based on a common length scale. For this analysis, L was set equal to 200 m so that the influence of advective transport and transient storage would be balanced (Runkel 2002).

Results

The investigational reaches varied across several significant characteristics (Table 1). Flow rate ranged over two orders of magnitude (0.82 L/s to 640 L/s). Impervious cover was quite high for all reaches, indicative of the urbanized nature of the watersheds. While Dead Run had significantly greater impervious cover, Valley Creek reaches had at least 13% impervious cover. All reaches would be considered to be at risk of impairment based on the percent impervious cover (Klein 1979). The extent of open canopy also varied greatly from 0 % (a reach with canopy shading over the entire length) to 100% (a reach with no canopy shading).

F_{med} varied widely from 1.08×10^{-4} to $2.50 \times 10^{-1.}$ Within the Dead Run reaches with some open canopy (D2 and D3), the seasonal variation in F_{med} was more than 8 times greater than the seasonal variation in reaches with no open canopy (Figure 3a). Similar differences were observed in the main stem of Valley Creek (Figure 3b) where the seasonal variation in F_{med} in reach V2 (57% open canopy) was 12 times greater than the seasonal variation in V1 (0% open canopy). The Valley Creek tributaries had slightly less, but still notable, seasonal variability (Figure 3c). The seasonal variability in F_{med} observed in V3 (79% open canopy) was almost two times greater than the seasonal variation observed in V4 (0% open canopy).

The data were examined both spatially (open canopy vs. closed canopy) and seasonally (spring vs. summer/fall) for statistical significance. A statistically significant seasonal difference was found in the open canopy reaches with spring F_{med} values being lower than the summer/fall values based on ANOVA (Table 2). There was no statistical difference in the summer/fall F_{med} values in open canopy reaches compared to closed canopy reaches. The closed canopy reaches were seasonally invariant as well.

Table 2. Statistical significance (*p)* of seasonal and canopy cover relationships based on ANOVA (KaleidaGraph v.3.6, Synergy Software, 2003). Statistically significant differences are assumed when p<0.05.

	Open Canopy: Spring (n=5)	**Closed Canopy: Summer/Fall (n=6)**
Open Canopy: Summer/Fall (n=5)	0.04	0.82
Closed Canopy: Spring (n=5)	0.14	0.62

When the data for all of the open reaches were combined, we found a statistically significant temporal relationship between F_{med} and month of the year as shown in Figure 4a while the values of F_{med} for the closed canopy reaches are not significantly related to month (Figure 4b).

Conclusions

Our results indicate that transient storage increased from spring to summer/fall in open canopy reaches, but not in closed canopy reaches. In the spring, transient storage played a small role in downstream transport in open canopy reaches. By summer, transient storage in open canopy reaches was statistically indistinguishable from transient storage in closed canopy reaches. This variation in transient storage may have important implications for nutrient and contaminant transformation and transport as well as stream ecosystem metabolism.

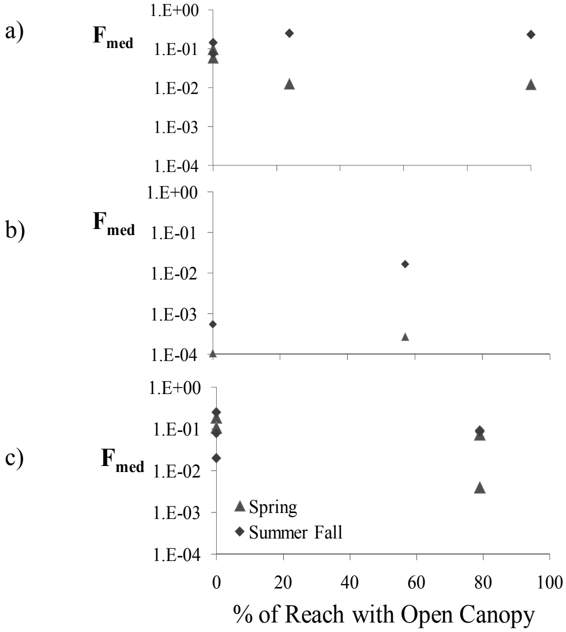

Figure 3. Relationship between F_{med} and the percent of the reach with an open canopy. (a) Dead Run (D1-D4) (b) Valley Creek Main Stem (V1-V2) (c) Valley Creek Tributaries (V3-V4)

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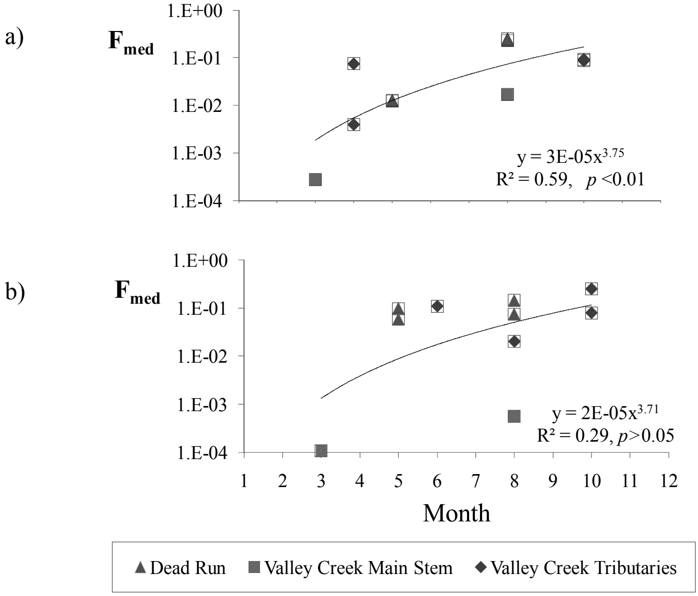

Figure 4. Temporal trend of F_{med}. (a) Open canopy reaches exhibit a statistically significant trend in which the month of the year explains 59% of the observed variation. (b) The variation of F_{med} in closed canopy reaches is not related to the month of the year.

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Hydrogeologic Testing, Engineering, and Start-up of a Gravity Drain System

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Abstract

This paper summarizes the system engineering, installation, and start-up of an innovative stormwater management system using a "Gravity Drain Field" subsequent to a 2008 concept paper on the subject by Lolcama and Gauffreau in ASCE Geotechnical Special Publication 178. The stormwater management concept resulted from a collaboration of hydrogeologists and geotechnical engineers as engineered drainage for disposal of large stormwater volumes into epikarstic bedrock. The concept provides compliance with recent NPDES regulations in karst terrain by utilizing a series of low pressure, Class V injection wells (gravity drains). The gravity drain engineered recharge system replicates the movement of stormwater into the deeper epikarstic flow conduits that was occurring at a site prior to development, with the exception of isolating the stormwater from the soil mantle to prevent sinkhole formations, and flow capacity management.

The concept has been developed into a working stormwater management system, and 19 Gravity Drains have been installed at a karst site located in the greater Philadelphia area. At this site, the method has the potential to recharge a volume of water greater than that of a 2-year storm event in a fully developed condition, which equates to 29.9 acre feet of stormwater, or 9.7 million gallons during each storm event. This paper discusses the selection of the gravity drain locations; the gravity drain and monitoring system layout; the hydrogeologic testing of the drains and well field array; the injection well and the drain field engineering specifications and installation; the automated remote hydrogeologic monitoring of the drain field

including water table and subsurface temperature; and the stormwater pre-treatment and conveyance to the drain field.

Introduction and Site Description

This paper follows the concept description by Lolcama and Gauffreau (2008), and discusses the hydrogeologic testing and selection of the individual gravity drains and monitoring well locations; the hydrogeologic testing of the multi-well array; the injection well and the drain field engineering specifications and installation; and the stormwater pre-treatment; and the features and operation of the automated remote hydrogeologic monitoring and notification capability, at a large commercial development site in the greater Philadelphia area.

On large sites undergoing development in karst terrain, the engineer is faced with the dilemma of how to manage significant volumes of stormwater runoff on a site where difficult ground conditions exist for infiltration. The NPDES permit regulations require that the difference between the post-construction stormwater runoff volume and pre-development runoff volume for the 2-year frequency storm event be managed on-site, emphasizing the use of BMPs to the greatest extent possible. From Lolcama and Gauffreau, the occurrence of “karst loss” into the bedrock results in larger volume differences that must be managed where fine-grained residual soils have relatively low infiltration rates. If one were to attempt rapid infiltration in this environment, the result would be impractically large infiltration BMPs that could also put nearby proposed buildings or other critical site features at risk from ground subsidence. However, by employing vertical Class-V injection wells (gravity drains) that transmit the stormwater directly into karstic bedrock, and by-passing the soil mantle, large volumes of stormwater can be managed successfully on-site, and the amount of off-site discharge is greatly reduced enabling the developer to meet or exceed the NPDES permitting requirements.

The concept has been developed into a stormwater management system with 19 gravity drains that have been installed into karstic permeability beneath the site. The system has the potential to recharge a volume of water greater than that from a 2-year storm event, which equals 29.9 acre feet of stormwater, or 9.7 million gallons per event.

Concept Feasibility Demonstration

The design of the gravity drain stormwater management system for the site had to be compatible with the established site concept design. All historical and recent geologic and hydrogeologic information about the site was compiled and reviewed for characteristics of the bedrock permeability. Historical and recent sinkholes were mapped, and a few active sinkholes were excavated to expose the rock throat and were injected with potable water for recharge capacity measurements.

The thickness of the overburden and the surface topography of the bedrock beneath the site were modeled from more than 260 test borings and pits, and geotechnical boreholes for surrounding roads and bridges. The discrete karst features of the bedrock were mapped by drilling 75 boreholes to depths of up to 150 feet below ground surface (bgs). The ambient water table elevation and the water injection capacity of each borehole in the karst bedrock were determined. Sustainable water recharge capacity ratings of individual 6 to 8 inch diameter test borings were several hundred to 2,300 gallons per minute (gpm). The water table was found to lie inside of the epikarst bedrock by up to 30 feet.

A model of widespread interconnected karstic permeability emerged for the site. The karst conduit network was most likely formed by slightly acidic groundwater flowing from the sandstone geologic formation onto the dolomite bedrock during a period of much lower water table. The corrosive groundwater would have spread out laterally and infiltrated the dolomite through permeable fracture lineaments that are found dissecting the property. A few of the lineaments developed deep karstic cutters due to the groundwater preferentially dissolving the more permeable vertical channel features. This mechanism of conduit formation in karst is described in detail by Palmer (2004). The cutters are interconnected horizontally with solutioned geologic beds and bedding plane partings. The result was an interconnected network of karst conduits passing through the bedrock, with the network hosting conduit flow to varying degrees depending on the amount of plugging with residual and transported sediment. The epikarst layer was found to be overlain by overburden between several feet and 41 feet thick. The discovery of the existence of the interconnected karstic permeability with large recharge capacity in selected areas of the site demonstrated the viability of the concept.

The Stormwater Injection System Location and Design

The initial design of a gravity drain stormwater management system called for two large lined stormwater ponds located near to each other and overlying a broad and deep epikarstic cutter in the dolomite near to the geologic contact with the sandstone unit. A number of drains were intended to be positioned around the perimeter of each pond to inject the pre-treated stormwater inflow. The area of the ponds had been the site of several historical sinkholes which had been demonstrated to accept sizable rates of recharge. Drilling and testing of the perimeter gravity drain locations showed that the bedrock permeability was insufficient at the proposed locations of the drains to support the gravity drain pond design, due largely to the plugged nature of the majority of the epikarst and deeper karst with terra rossa sediment and debris in this localized area. However, in the southern portion of the property, which is also underlain by bedrock with mature karst features, testing of locations for gravity drains which were intended to inject runoff from the roofs of the buildings was on-going and had encountered relatively large recharge capacities in the bedrock. The stormwater design was modified, removing the two gravity drain ponds, and combining the ponds into one large mid-pond where the large majority of site stormwater would be pre-treated, collected, and conveyed to a permanent gravity drain field approximately 1,000 feet away in the southwest quadrant of the site.

Description of the Injection Well Array

A 3-acre exploration area in the southwest quadrant of the site mentioned above was marked with up to 60 possible locations to be drilled and tested for injection capacity. A reconnaissance-type, rapid drilling and injection testing method was devised to a depth of up to 100 feet, and an initial phase of drilling and testing was commenced. A number of boreholes located at the north, south, and east of the investigation area were eliminated as candidate drain locations immediately after drilling due to epikarstic depressions resulting in insufficient thickness of bedrock above the ambient water table. During the injection of stormwater to the karst aquifer, maintaining the water table deep inside of the bedrock is paramount as a protective measure for the overburden to reduce the risk from sinkhole formation. Recharge testing was completed in the remaining boreholes. The injection test results showed large, sustained gravity recharge capacity, with one well at 540 gpm; ten wells with recharge capacities in the range of 1,000 to 1,600 gpm; and one well had a capacity in excess of 2,300 gpm. The capacities are for 6 and 8 inch diameter test wells; a multiplier of 1.2 was applied to these numbers to estimate capacity for the planned 12-inch Class V wells.

A second phase of drilling and testing came out of the success of the first phase, during which a number of successful injection tests were completed. Drilling was concluded with a total of 29 test boreholes completed in two phases, of which 19 boreholes had sufficient injection capacity to be developed into permanent gravity drains. The selected drain field occupied an area of roughly one acre out of the 3 acres that were drilled and tested. The quality of the rock skeleton was assessed for each drain location, and a determination was made that the karstified bedrock would resist densification during stormwater injection. The solid nature of the rock skeleton, and the typical karst formations in bedrock, are shown in the hydrogeologic cross section of Figure 1. A minimum separation distance between boreholes of 50 feet was established as a working guideline. The distance was selected to lessen the interference effects of one well on the surrounding wells during stormwater injection, thus enabling greater rates of recharge.

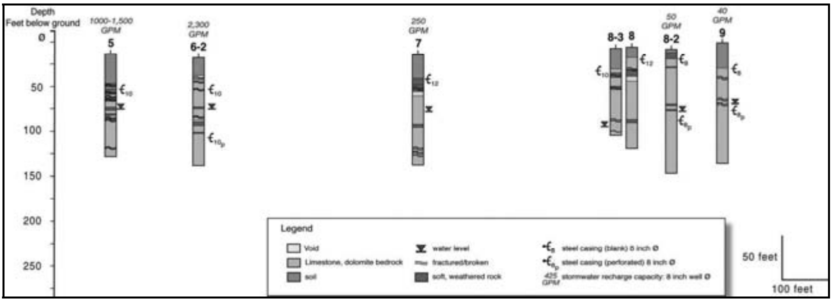

Figure 1. Geologic cross section showing rock skeleton and karst features

Individual Well Capacity Testing

Water recharge (capacity) testing was performed after the borehole was sounded and verified as open. Potable water was conveyed to each of the tested pilot holes by a 6-inch pump with a maximum capacity of 2,300 gpm. Up to 20,000 gallons of potable water, at a measured flow rate of up to 2,300 gpm, were delivered to each pilot hole with the rate of injection depending on the groundwater table response. The flow rate was measured using a flow meter and was controlled with a gate valve at the top of the pilot hole casing. The recharge testing of the individual gravity drain wells was performed at a continuous rate for a period of time, separated by step increases in the rate. The recharge rate to the well was held steady for a period of time until steady-state water level in the well was reached, at which time the flow rate was increased under the guidance of the Project Hydrogeologist. The flow rate was increased until a pre-selected maximum level in the water level in the injection well was achieved corresponding to the water level in the borehole being well below the top of the epikarst bedrock. After the completion of each test, the groundwater table recovery in the epikarst was monitored.

The required injection capacity is the calculated difference between the post-development runoff and pre-development runoff for the 2 year 24 hour storm event, or 29.9 acre-feet. The required design flow rate to the gravity drains is based upon the 2 year storm peak runoff discharge rate of 41.48 cfs. The rated capacities of the 19-well drain field fell into the ranges: 1 drain at 170 gpm; 5 drains at 700-900 gpm; 7 drains at 1,000 to 1,500 gpm; 5 drains at 1,500 to 2,000 gpm; and 1 drain at 2,300 gpm.

Multi-well Capacity Testing

A multi-well test was performed after 13 individual drain locations had been successfully tested. The objective was to demonstrate that the gravity drain field could accept stormwater at a recharge rate equivalent to a 2 year storm event with the water table remaining well below the top of the epikarst bedrock. At the time of the testing in 2008, 13 locations had been selected for gravity drains. The pilot boreholes that were selected for multi-well testing were improved by cleaning out sediment to enable water to enter the deeper karstic permeability. The field testing apparatus for the multi-well test is shown in Figure 2. Three water storage bladders each holding 20,000 gallons supplied water to three 6 inch diesel pumps capable of pumping about 2,300 gpm under low pressure head conditions. A special manifold was fabricated to convey the discharge from the pumps into 7 outlets which were piped directly to the pilot holes. The flow rate to each pilot hole was manipulated using an in-line valve. Flow meters were placed in-line to monitor the rate of flow to individual boreholes. In-Situ Level Troll equipment was installed into a number of outlying boreholes that were being monitored for water table response. The water level in each of the boreholes being injected with water was recorded by a scientist/engineer, and the Project Hydrogeologist directed the testing sequence. Once pumping was commenced, the rate of water injection to each well was continued until a steady state water level had been reached, after which the injection rate was increased in several steps until the pre-determined maximum elevation of the water table within each of the 7 pilot holes had been reached.

Figure 2. Multi-well injection testing

The entire injection test was accomplished in roughly 30 minutes. The successful injection testing of the north-cluster using 7 pilot holes demonstrated that the epikarst throughout this area has the capacity to accept 5,900 gpm of recharge, while the water table elevation within the epikarst remained far below a pre-determined threshold elevation during testing. A contour representation of the water table mound or rise during multi-well injection testing is shown in Figure 3. In addition, each pilot borehole was characterized with a specific injection capacity value which was used to calculate the additional expected rise in the water table during the full 2-year-storm recharge rate. The amount of additional rise was estimated by dividing the additional required rate of stormwater recharge in gallons per minute by the specific injection capacity in gallons per minute/foot of rise. The estimated amount of rise is added to the multi-well test result for the borehole, and this amount was compared to the pre-determined water table threshold. It was demonstrated to the satisfaction of the Project Hydrogeologist that the multi-well test area could operate at the 2 year storm rate of recharge with an acceptable rise in the water table. Injecting millions of gallons of water into the ground to test the gravity drain field under the full 2-year storm recharge rate was not necessary, and was technically impossible.

The 5-drain cluster, located to the south of the drains discussed above, can be expected to have a similar to slightly smaller area of water table influence given the 5-drains with similar aggregate recharge rate capacity as compared to the north cluster. The two zones of influence from the north and the south clusters can be expected to commingle; the magnitude of the effect of one zone on the other zone will be relatively small.

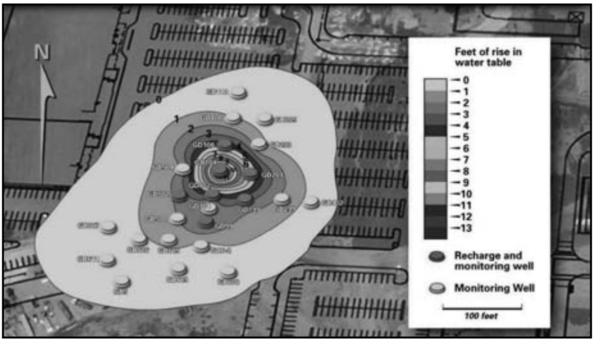

Figure 3. Measured water table mound during multi-well potable water injection

Gravity Drain and Monitoring Well Design and Installation

The gravity drain generalized design is shown in Figure 4. The 12 inch diameter gravity drain is comprised of a 12-inch blank steel casing that extends through the overburden and a 12-inch stainless steel screen section that is installed through the epikarst bedrock layer and into the deeper karst bedrock, to the recommended depth. The screen is not covered with a granular filter pack, which would tend to restrict flow outwards into the karst bedrock. The annular space through the overburden is grout-sealed to control water seepage and the migration of fines downward around the drain, which mitigates the risk of sinkhole formation at that location. The annular seal is supported by a cement-basket which is expanded to conform to the shape of the borehole. A groundwater piezometer has been installed 5 to 10 feet from each gravity drain, for water table monitoring purposes.

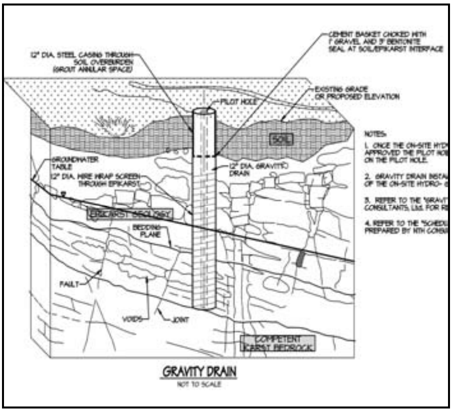

Figure 4. Generalized Gravity Drain design

The boreholes for the gravity drains were installed using the Symmetrix air-rotary drilling equipment and techniques by Rotex. The method used an inner drill rod equipped with a carbide-button bit on a 16 inch diameter down-the-hole hammer, and an outer steel casing with a casing shoe and a ring-bit. The ring bit cuts a slightly oversized borehole allowing the casing to follow it down the hole. The drill rods and hammer and bit were removed from the completed borehole. The pre-fabricated stainless steel well screen with welded end cap was suspended in the cased borehole, and blank steel casing lengths and the cement basket were welded on, and the well assembly was lowered into position in the borehole. Screen lengths varied from 25 to 85 feet depending on the thickness of the zone of conduit flow formations in the bedrock.

Stormwater Conveyance Design and Flow Control

Prior to entering the gravity drain field, stormwater runoff from the site is conveyed in a controlled manner through various conventional drainage systems. All stormwater is pre-treated by an oil/water separator just prior to entering the Mid-pond. These separators are maintained on a regular basis and are part of the spill control system used to prevent contamination of the groundwater. The oil/water separators are described in more detail below. After collecting in the Mid-pond, the stormwater can access the gravity drain discharge pipeline via an intake headwall. A service manhole and slide gate valve is positioned along the pipeline near the basin to adjust or cease the flow rate of stormwater that is permitted to access the gravity drain field acting as another control to limit water from entering the gravity drain field in the event of a spill.

Within the gravity drain field itself, each connecting pipeline and gravity drain is designed with the same invert/rim elevation to permit an even distribution and near simultaneous recharge of all drains. In addition, each drain has been fitted with an intake riser and screen designed to control the recharge rate to its pre-determined capacity. Several redundancy factors are also incorporated into the system to accommodate flow rates exceeding the 2-year design storm, including two overflow pipelines discharging to a lower, very large storage basin. Discharge rates through these pipelines are monitored automatically by flow meters to verify the system’s functionality.

Remote Automated Hydrogeologic Monitoring and Reporting

The epikarstic water table level within the drain field is maintained within the epikarst bedrock to minimize the risk of conditions developing that could lead to sinkhole formation in the overburden. Mounding of the water table into the overburden layer overlying the karst bedrock could destabilize the ground by scouring and soil piping. These conditions could occur if the gravity drain field were operated without monitoring and management during very large storms, or during very closely timed storms. Under these conditions, the stormwater flow rate to the drains would be reduced using the main flow-control valve to a pre-determined quantity to provide the aquifer time to recover by dissipating the stormwater. The water table response to the flow rate reduction is monitored by the Project Hydrogeologist to verify that the water table level has been restored, prior to re-establishing recharge to the drain field. The monitoring data can also provide an indication of deterioration of a drain by fouling or plugging of the well screen, or by accumulation of sediment in the screen as the result of sloughing of sediment fill material from the interior of karstic caverns.

The aquifer conditions of water table and temperature within the gravity drain field are monitored automatically using In-Situ Level Troll down-the-hole sensors, and Troll Link cellular telemetry to transmit data to secure, off-site data storage and processing center. The power requirement of the Troll Link hardware is provided by solar-electric panels which maintain a charge on deep cycle batteries. On-site data backup is accomplished using dataloggers which are also located down-the-hole. Remote access to the data center is accomplished through the world-wide-web. The monitoring equipment set-up is shown in Figure 5.

Figure 5. Remote automated electronic monitoring equipment setup

Early warning indicators of a developing condition, and an alarm of an imminent condition, are automatically transmitted by the data center using email/text message/phone call. A developing condition would be an epikarst water table that is approaching a maximum elevation threshold; the thresholds are pre-determined by the Project Hydrogeologist. Several times a day, the data center performs an automatic comparison of all new data with a pre-set threshold value, and if the water level rises upwards to approach the warning threshold, a “warning” text message is broadcast, and when the level rises above the threshold, an “alarm” message is broadcast. And finally, when the parameter falls back below the threshold, an “alarm over” message is broadcast. Retrieval of the backup data can be accomplished at the Site by cabling to each of the dataloggers with a computer and harvesting the accumulated data from memory.

The overall data quality, reliability, and availability in real-time is greatly improved using the automated monitoring system described above. Data availability is increased to “full-time and on-demand”, which enables more insight into system behavior, and for much less cost than manual monitoring.

Stormwater Pre-treatment

The conveyance system incorporates several methods to pre-treat the stormwater before it is introduced to the epikarst via the gravity drains, as outlined in the development’s Operations and Maintenance Manual that was required as part of the NPDES process. Regular sweeping of paved surfaces is a recognized Best Management Practice (BMP) for limiting debris, sediments, etc. that may be introduced to the stormwater runoff. Once in the site piping network, stormwater will also pass through an oil/water separator unit prior to entering the Mid-pond. The units will remove suspended sediments, floatables, and hydrocarbons from the stormwater. Once in the Mid-pond, additional solids can settle out of the stormwater prior to rising to a sufficient elevation to enter the gravity drain intake pipeline. Finally, after the stormwater has entered the gravity drain piping network but before reaching the gravity drains themselves, it must pass through an intake riser and screen that is outfitted above each drain to filter large-scale floatables or other debris (such as leaves) and keep them from entering the gravity drain and underlying epikarst.

System Start-up and Performance

The gravity drain system has performed extremely well during the 7 month period of operation since system startup in mid-December 2010. The system has met and exceeded our performance expectations, having managed roughly 50 million gallons of pre-treated stormwater runoff during a period of time when the site did receive a substantial number of heavy rainstorms. About 16 inches of rainfall occurred to the site during the startup period of monitoring, which stressed the system beyond the anticipated stormwater volumes, and frequency of storm occurrence. The automated hydrologic and hydrogeologic monitoring equipment and datacenters have performed extremely well; the field equipment and auto-notification technology has proven to be very reliable and robust, even under challenging hydrogeologic conditions. The auto-notification feature has exceeded our expectations for enabling the project hydrogeologist to manage the stormwater recharge rate to the karst aquifer, to maintain stable operating conditions in the gravity drain field. The quality of the water level data has been excellent, and the data-center utilities for secure and continuous data access, along with automated data graphing, have proven to be well-suited to the needs of the project.

Final Remarks

New technical innovations in stormwater management are continually being sought as urban and suburban areas are stressed with increasing runoff. Land developers are being faced with the challenge of managing on-site the difference between pre and post development runoff for a 2-year storm. This case study arose out of such a need, and demonstrates the following points. Firstly, from a technical perspective, geologic formations that are well known for geohazard problems (karst), when combined with a well-considered design and careful implementation with real time monitoring, can be a key component to a safe, high-performance stormwater disposal system. Secondly, a thorough investigation of the hydrogeologic and geotechnical properties of a site is paramount to establishing accurate and lasting performance expectations for the design and the operating and maintenance procedures for the long term. And finally, when undertaking technically challenging and fast-paced projects such as this, mutual trust and open communication and placing all of the stakeholders on an equal footing can be the difference between success and failure of the project.

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From Gray to Green, Onondaga County's Green Strategy Addressing CSOs

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Abstract

Onondaga County, New York, in partnership with the City of Syracuse, has a substantial financial commitment to using green procedures to address its longstanding CSO issues. Its court ordered program shifts from building centralized industrial wastewater treatment structures and massive pipe storage systems to using decentralized green infrastructure (GI) approaches to hold, infiltrate and clean polluted stormwater runoff and reduce CSOs. Specifically, this order stemmed from an extended official negotiation process among the County, New York State Department of Environmental Conservation (DEC), Atlantic States Legal Foundation, Inc. (ASLF), and various stakeholders and community advocates, and it requires Onondaga County to apply green infrastructure approaches, as a complement to gray projects, to reduce CSO volume and meet water quality standards. This has put this community in the forefront nationwide for addressing stormwater and CSOs.

Origination and Evolution of ACJ.

Onondaga Lake is located in Central New York, within Onondaga County, and is 4.6 miles in length and one mile in width. Its 285 square mile drainage basin includes the greater part of both the City of Syracuse and Onondaga County. Onondaga Lake has been important to the human habitation of central New York and is a sacred place for six Indian Nations including the Onondaga since the Haudenosaunee (Iroquois) Confederacy formed on the lake shore in the 17th century. Unfortunately, Onondaga Lake has experienced a long history of pollution from both industrial operations and municipal wastewater discharges around the lake and became one of the most polluted lakes in America. Today, Onondaga Lake has received an intensive cleanup with nearly $1 billion in investment of public and private funds. Although much work remains, the water quality is progressively getting better with all indicator parameters, both chemical and biological, showing great improvement.

The Metropolitan Syracuse Wastewater Treatment Plant (METRO), is located on the southern shore of Onondaga Lake. Originally called Syracuse Sewage Treatment Plant, METRO was transferred from the City to Onondaga County in 1955, along with the storm drains in the city. METRO contributes about 20 percent of the annual inflow into Onondaga Lake, with much greater percentages during seasonal low flows. This is a significant proportion compared with other lakes nationwide and is one of the main sources of pollution to the lake.[1] In addition, during wet weather, CSO discharges from many points discharge directly into surface water bodies in the combined sewer areas, which then flow into the Lake, exacerbating the lake pollution.

In 1988, Atlantic States Legal Foundation (ASLF), later joined by the New York State Department of Environmental Conservation (DEC), filed a lawsuit under the Clean Water Act against Onondaga County for numerous violations of state and federal water pollution laws which had resulted in severe water quality deterioration in Onondaga Lake and some of its tributaries. The litigation was settled through the METRO Consent Judgment the following year, but due to continued delays in making progress to correct the problems, the parties had further intensive negotiations and ultimately replaced the initial settlement with a new agreement called the Amended Consent Judgment (ACJ) in 1998. The ACJ set forth in great detail nearly thirty projects that the County must complete, along with an extensive monitoring program, in order to comply with the law and meet water quality standards – the ultimate test of compliance. In the last decade, spending to improve the water quality of the Lake basin and achieve full compliance with state and federal water quality regulations has cost Onondaga County some $350 million to upgrade its treatment plant, facilities, and sewer system. The County's strategy for dealing with its CSO problems was largely centered on the construction of four new Regional Treatment Facilities (RTFs) in four neighborhoods within the City of Syracuse. However, this construction of RTFs was bitterly opposed by many stakeholders and City officials for its adverse impacts to these neighborhoods, inadequacy of treatment,[2] and extravagant cost. Residents opposed RTFs for their deleterious effects on neighborhoods and their high costs, as well as being an inadequate solution to the problem. The public never opposed spending to control known problems with the sewer system and in fact took the lead in trying to remediate and improve water quality in the various lake tributaries that received the discharges from the CSO overflows. Opposition was led by neighbors of the lone RTF constructed and the community disruption finally reached a political tipping point, and no more such

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[1] This paper only concerns itself with conventional pollutants coming from the METRO system. The lake is also a listed Super-fund site with many sub-sites. These are being remediated under a different program.

[2] The RTF might or might not meet the EPA CSO policy requirement to be at least as effective as primary sewage treatment.

plants are now considered. The remaining mixture of green and gray projects still to be constructed will cost an additional estimated \$275,000,000[3].

Meanwhile, applications of innovative green infrastructure approaches for CSO reduction and nonpoint pollution removal have been showcased in other places around the country such as Portland, OR, Philadelphia, PA, and Chicago, IL, and EPA has started promoting the use of green infrastructure, touting the variety of benefits GI delivers in addition to CSO volume reduction and stormwater mitigation.

Switch from Gray to Green

Considering the various factors discussed above, combined with new political opportunities, ASLF and others re-opened their campaign for better alternatives than were in the ACJ. The effort was begun in mid-2007, when ASLF and a representative of the Onondaga Nation, who have been actively involved in the lake improvement process, approached the new NYS DEC Commissioner to revisit options[4]. Later that year, in the November elections, Joanne Mahoney was elected[5] County Executive and took office in January of 2008. She had heard the objections to the construction of RTFs from the community in her previous role on the City Council and understood the need to look for better, cheaper solutions. After a deliberative process she chose to change the county's sewer policies to superior alternatives. She then became the biggest supporter for the application of green infrastructure in Syracuse and Onondaga County. Led by ASLF and Onondaga Nation representatives, the ACJ parties began to investigate better alternatives with the help and encouragement of both the state and federal governments. County Executive Mahoney agreed with making changes to the program and encouraged looking into new green approaches. After rounds of discussion, the County delayed awarding new contracts for the construction of another RTF and finally cancelled the construction, even though the site work had begun and bids for construction had been received. At the same time, ASLF and the Onondaga Nation brought green infrastructure experts to Syracuse, who gave presentations on the technical and regulatory benefits and feasibility of green infrastructure and its application to this community. In the spring of 2008, NYS DEC agreed to consider extending ACJ deadlines which further enabled the discussion about new alternatives. To facilitate the discussion and study, from spring to fall 2008, six committees were formed by ACJ parties, with the Legal and Financial committees chaired by NYS DEC, the Gray and Policy committees chaired by Onondaga County, and the Green and Public involvement committees chaired by ASLF.

A gradual consensus was reached among all parties by early 2009. The County then decided to move forward and hired CH2M HILL, an engineering firm

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[3] No attempt has been made to bring all of the expenditures and estimated expenditures up to 2011 dollars.

[4] This effort was also enhanced by US EPA's giving more scrutiny under the National Environmental Protection Act before additional federal funds could be released for RTFs.

[5] Ms. Mahoney has subsequently been re-elected, running without opposition.

experienced in green infrastructure, to do a feasibility study and the programmatic planning that was needed for presentation to the Federal district court[6]. The result, after long discussions and protracted negotiations, was the first court decision of its kind in the United States, which requires the County to employ cutting-edge green infrastructure solutions to combat its longstanding CSO problems as well as use more benign underground storage for achieving, by 2018, an eventual 95% capture of CSOs. The new agreement was presented to the federal district court as the Fourth Stipulation[7] to the ACJ and it was approved in November 2009. The new agreement requires that green infrastructure capture 6.3% of total annual CSO volume, an equivalent of about 250 million gallons per year. Onondaga County halted its plan to construct more large-scale regional treatment facilities; instead, those allocated funds will be used to carry out a decentralized approach of using green infrastructure mechanisms in combination with other traditional gray infrastructure for stormwater management and CSO abatement. The Fourth Stipulation of the ACJ now makes the requirements for green infrastructure legally binding on Onondaga County. Onondaga County has thus moved to the forefront in the nation for using innovative, systematic green strategies to address stormwater and CSO management.

Implementation of the ACJ Fourth Stipulation's Green Components

Once the Fourth Stipulation was entered by the Court, the County and its primary consulting firm, CH2M HILL, started developing and implementing green infrastructure projects in the sewersheds with combined sewer systems. An umbrella green infrastructure campaign, *Save the Rain*[8], was established, under which all work conducted by the County and its consultants is coordinated. Programs have been developed to promote the implementation of green infrastructure projects on both public and private properties.

Programs on Public Property. The public programs include deployment of green infrastructure projects on streets and public right-of-ways, city parks/open space, publicly owned or sizable vacant lots, and city and county owned parking lots and public facilities[9]. High priority has also been given to schools and libraries that, in addition to providing for water capture, can serve as locations for public education and awareness. The City of Syracuse and Onondaga County have reached an agreement which enables the County to construct green projects on city properties with no or minimal cost to the City, and the County's consultants work collaboratively with City officials and engineers on planning, design and construction of green projects. The County and City also developed a joint Urban Forestry Program which incorporates the City's goal of increasing urban tree canopy in Syracuse into the County's Save the Rain program, with a goal of planting 8,500 trees

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[6] The new plan would be a change from the previous court approved ACJ and therefore changes would need to be brought before the Court for approval.

[7] Available at http://www.onondagalake.org/docs/ACJSTIPsigned16November2009.pdf. Detailed descriptions, technical plans, and related materials can be found on numerous websites, and all documents may be viewed, by appointment, at the ASLF office in Syracuse, NY.

[8] See the *Save the Rain* website, http://www.savetherain.us.

[9] As feasible state and federal owned parcels are also being evaluated for GI.

within combined sewersheds by 2018. In addition, another important item on the County's Save the Rain agenda is a collaboration with the City to revise City ordinances for redevelopment projects, making capture of the first inch of rainfall a requirement for those projects' stormwater management plan.

Programs on Private Property. Most land in the sewershed is privately owned, and many of these properties also capture stormwater. For the private sector, Save the Rain has an ongoing aggressive public campaign to inform owners and renters of the new program, and it also makes several green incentives available for private owners encouraging them to apply green infrastructure technologies on their property. A series of rain barrel programs, including free rain barrels for residents, rain barrel workshops and green infrastructure workshops and design charettes, as part of Save the Rain outreach campaign, have attracted hundreds of participants and distributed over 300 rain barrels in the combined sewersheds by August 2011. The Green Improvement Fund, an incentive that provides financial assistance for the installation of GI projects on eligible privately owned properties (commercial, business, and not-for-profit owned properties) in combined sewersheds, has successfully funded the construction of 18 projects by the end of 2011, with another 20 projects in progress and dozens of applications for funding[10].

2011 was a remarkable year for the Save the Rain Program. In April, Onondaga County, with the City of Syracuse, was named one of the country's Top 10 leaders in green infrastructure by EPA, and became the EPA's "Green Infrastructure Partner" in promoting innovative green approaches to managing wet weather. 2011 was the first full year of project implementation and featured the 'Project 50' campaign to build 50 separate and distinct GI projects. By the end of 2011, 30 GI projects were completed and 30 under construction. The 2011 construction season also provided several high-profile signature projects including a 60,000 square foot green roof system at the Onondaga County OnCenter complex, one of the largest green roofs in the country; an innovative water re-use system at the War Memorial Arena that converts captured stormwater into ice for the Syracuse Crunch AHL hockey team; the conversion of the Skiddy Park basketball courts to green courts via a partnership with the Boeheim Foundation "Courts 4 Kids" program; and the development of several "green street" projects throughout neighborhoods in Syracuse. In late 2011, the National Resources Defense Council included Onondaga County as a case study for green infrastructure implementation in its publication *Rooftops to Rivers II: Green Strategies for Controlling Stormwater and Combined Sewer Overflows*[11]. The green efforts of Onondaga County were further recognized nationwide with various officials, CH2M HILL, ASLF, etc. being asked to discuss the program at national conferences.

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[10] The Green Improvement Fund (GIF) program has been very successful. Details of it and the application can be seen on the website. See footnote 9.

[11] Available at http://www.nrdc.org/water/pollution/rooftopsii/

Road to Success

Onondaga Lake shows the success the public can have in making use of the Citizen Suit provision (Section 505) of the Clean Water Act. In this case, the lawsuit led toward the protection and enhancement of a key polluted water resource and, after many years of negotiations, converting one of the worst polluted bodies of water into one where the chemical and biological integrity of Onondaga Lake is close to being restored. The court approved settlement document has evolved with the approval of the Fourth Stipulation to the ACJ, and this has demonstrated how more favorable solutions can ensue with support from community advocates, inter-administrative collaboration, and the political will of elected officials. The Fourth stipulation has brought this case to another level.

Green in Place of Gray. The transition from massive construction of gray projects to a more benign green/gray infrastructure solution without building any more RTFs was an extended process. The following factors in this process are critical from the beginning to make this transition possible.

- New technologies and knowledge provided viable options that could be explored. That these had track records in other locations was crucial. Green infrastructure technologies in other places around the country showed that these innovative applications were doable here;
- Public support and community advocacy for green alternatives, as opposed to their bitter opposition to the original gray plan to build more RTFs which would be disruptive to the neighborhood;
- The vision of decision makers: officials on state and county levels must be open to innovative, beneficial green approaches, which in this case allowed the intensive negotiations between ACJ parties to happen;
- Collaboration across administrations and ACJ parties: in preparation for the Fourth Stipulation to the ACJ the six committees, consisting of members not only from the ACJ parties but also experts from the community, gathered community input that was critical to the success of the parties' agreement to the ACJ's revision.
- Professional technical support from experts which helped the parties lay out the green plan and present its feasibility and additional benefits to the federal district court judges;
- Time for these negotiations was limited; meeting mandatory milestones forced the parties to come to an amended agreement in a matter of weeks, preventing a prolonged negotiating process;
- Green infrastructure’s ancillary benefits in addition to stormwater management: perceived economic and environmental revenue from investing in green infrastructure were in accord with City and County sustainable planning for the future, and gained support from all levels.

Challenges in Implementation Process of Green. The implementation of Save the Rain green infrastructure projects in Onondaga County has demonstrated numerous success stories. However, changing the program from the largely unpopular RTFs to a combined gray / green strategy requires an altogether different mind set by the County, its consultants, regulators, and the public. Implementing a relatively few large scale projects is logistically much easier than constructing many, many much smaller projects.

The American system for dealing with environmental issues has evolved into one where standard practice creates a framework something like the following:

- Identify a problem. This can happen by the property owner, local government entity responsible, the regulatory community, an environmental NGO, or private citizens.
- Detail the extent and seriousness of the problem. This may or may not happen within a formal judicial proceeding.
- Initiate investigations into a remedy. Usually the "defendant" hires consultants to investigate and design solutions. Larger entities have more in-house expertise and are more involved than smaller entities who give a freer hand to their chosen consultants[12].
- Implement the chosen remedy. This can involve regulators, the courts, and various stakeholder groups depending on the actual issue and the level of public interest[13].
- Completion of the project(s). This involves satisfying the regulators, court, public and may or may not involve continued monitoring.

All of these steps are, at least in theory, routine and straight forward when only a few large projects need to be designed, built, and maintained. Once we switch to many small projects things get very complex, very quickly. When green infrastructure projects are planned, things get even more interesting because you start "designing with nature" while using living organisms to do the work in many locations. Also, large projects are built on land acquired by the constructing agency and are thus public; many dispersed projects, by their very nature, must be placed on private land and in someone's back yard. For the small dispersed green projects to be designed, built, and function effectively over time, there needs to be active cooperation and buy-ins from communities in which the project(s) is (are) located. The following are primary questions and challenges that implementation of green infrastructure may encounter.

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[12] Most governmental units rely on consultants to do all the heavy lifting. These consultants are motivated by profit and these usually lead them to suggest similar solutions to all problems regardless of the nuanced local situations. These solutions are often relatively easy to design and construct with little consideration for long term operating costs, ecosystems, or public support. Regulators like the tried and true methods and so permitting and related issues are simpler as well.

[13] Large scale projects, in theory, need to get full environmental review under either the National Environmental Policy Act or state equivalents depending on who is funding the project. Often, however, under the guise that pollution control is a benefit to the environment, little or no review and looking at alternatives is performed.

Green Infrastructure Design: What level of design detail and bidding requirements go with small dispersed projects? And do all green infrastructure projects have to go through a strict, standard bidding process in order to get contractors for construction, which requires standard design packages with all engineering details for those projects? In Onondaga County, some modifications have been made to the procedure; for example, a "Term Contract" has been developed for a contractor to bid on construction of similar small projects. We question the desirability for all small projects such as rain gardens to have standard design details and be forced through the full bidding procedure[14].

Green Infrastructure Installation and Maintenance: Following the above discussion, for installation of small green infrastructure projects there should be opportunities for local community members to take over responsibility and to participate in these projects in their backyards, instead of going through a standard bidding procedure for hiring an outside contractor (outside of local and neighborhood individuals). Job creation for local residents has been mentioned as one of the outstanding benefits for local communities, particularly for those with a high unemployment rate. Green job training has become an item on many institutes' agenda. In Syracuse and Onondaga County, several training programs are available for community members. However, an awkward situation is not uncommon here: the trainees, after having received training from those programs, are still unemployed. This presents the challenge to make opportunities available for the local work force that truly benefits local communities.

Community Support and Buy-ins: Most land in a city is privately owned and so if you are going to control stormwater most of that drains from private property. In an older city such as Syracuse, where there is little new construction, capture of stormwater must be by retrofitting[15]. The County, therefore, initiated incentives to encourage private landowners to deploy green infrastructure on their property through the decision to fund, outright[16], those programs on non-residential private properties within the relevant combined sewersheds. However, getting private owners to assist and guarantee fully maintaining these green improvements on both their own and adjacent properties is another challenge. It may be accomplished by having local residents or organized volunteers to conduct regular maintenance tasks, which will require wide acceptance of green and stimuli for participation.

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[14] Federal, state, and local procurement policies are often very rigid and out of date regarding flexibility needed for many small projects. Higher cost thresholds and other changes should be considered in these procedures. Related issues also arise as there is a desire to employ local people in "green jobs programs," but these well intended practices often cannot be met.

[15] The paucity of new construction negates the eventual effectiveness in the MS4 program to alleviate stormwater issues. Whenever new or renovation construction trips the thresholds of that program, it is implemented and enforced here as well, we hope, across the nation.

[16] See previous reference to the GIF program. In the future, the County will gradually decrease this incentive program from present 100% reimbursement to lower and lower amounts as the program matures and we are closer to our final 2018 goals.

Design with Nature: How do you ensure that proper plant materials are being utilized? And how do you even determine what proper plant materials are? This becomes no longer just an engineering decision, but also involves ecological restoration issues, proper procurement to optimize chances for survival, and understanding life cycle needs of the plants. As an anecdote to this discussion we recently had to blow the whistle on another project in Syracuse where a contractor planted several thousand highly invasive Japanese honeysuckles along a stretch being naturalized. Public opposition to this got the plants removed and replaced by an appropriate native plant[17].

Compliance: Many small projects create compliance headaches for regulators. Large projects are built with monitoring "ports," enabling fairly easy diagnostic methodologies to see if they are working. Green infrastructure can be monitored but each project needs its own testing protocols that might not easily be agreed upon by everyone. Overall success of the program is also difficult to monitor, and even such a fundamental issue as how to demonstrate that you are meeting water standards in fast moving streams is by no means agreed upon. An additional complication is how you aggregate these small projects so that you can prove that the overall system is meeting its capture and treat goals. The standard models used for evaluating stormwater and CSO issues are fairly broad based and adapting them to GI is not easy.

In conclusion, the great benefits of green versus gray must be incorporated into the equation and used as a mechanism for promoting green. Our society likes to simplify problems and their solutions into different components that are never one dimensional even if they are treated as such. Meeting water quality standards can create many opportunities for improving the quality of life for human and non-human organisms and help lead us toward the goal of a sustainable community. Restoring our nation's waters to biological integrity is a daunting task; America has spent more on this than any other non-military expenditure. As we get closer to completing these projects, and as we learn more about the affected ecosystems, we realize that our original program may have been inadequate.

Opportunities in the Future

Onondaga County has begun expanding its Save the Rain green infrastructure program beyond the boundary of the urban combined sewer area by allocating an initial $3,000,000 to fund green projects in the suburban towns surrounding Syracuse[18]. At the same time, inter-municipal collaboration between the County and the City of Syracuse on green infrastructure program development at all levels is

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[17] In some cases, engineers, landscape design professionals, and even urban foresters still either disregard the use of native plants or are actually hostile. The many arguments pro and con will not be further spelled out here, but the need to consider urban ecological issues and even how the City fits within a regional ecosystem is very important and must be considered.

[18] For more information, please visit http://savetherain.us/suburban-gip-announcement/

making progress. Both the County and the City are seeing the green infrastructure program as an opportunity to move toward a future of sustainability.

Economic Sustainability. The way we look at and solve "problems" purposely does not look at the connectedness of these problems. For example, finances to upgrade water facilities usually come from either federal or state water pollution control appropriations or from user fees. Occasionally, funds can be procured from housing, transportation or economic development sources when the nexus is strong enough. However, the way government and private sector programs operate normally provide no incentives to broaden the rationale and funding for programs so that they are more encompassing of the longer term needs of the community.

The green infrastructure approach, which has demonstrated its multifaceted benefits in both the short term and long term sustainable community development process, may strengthen and broaden this connection and attract more external investment and funds for new development and retrofitting in the city. Improvements can also happen from inside out. Save the Rain has an ongoing Vacant Lot program which utilizes vacant parcels within combined sewersheds for green infrastructure projects capturing stormwater. Investigation and successful implementation of green projects on those eyesores has led to further discussions between the County and the City about integrating green infrastructure planning on vacant lots with the City's sustainable planning process. This provides another option to consider when it comes to management and reclamation of numerous vacant lots in cities like Syracuse who have experienced dramatic population decline. Converting vacant lots to more productive green uses helps in the solution to stormwater and CSO issues, but has many additional benefits. Entire conferences are now devoted to this subject and we will be writing about this in subsequent papers.

Another interesting possibility that green infrastructure brings to an older city such as Syracuse is the possibility of job training and utilization of underemployed inner city workers for implementing and maintaining green infrastructure. The green infrastructure program has generated and will generate more relevant green businesses while creating jobs for local communities. There are numerous unemployed or underemployed categories of residents who might benefit from these jobs. Suffice it to say that working outdoors growing trees, fiber, fruit and vegetables, not to say other types of GI maintenance, can led to highly satisfying, living wage entrepreneurial vocations.

Environmental Sustainability. Green infrastructure uses or mimics natural processes to manage stormwater. Most green infrastructure projects involve the planting of live plant materials often lacking in urban areas. In the planning and design process, native plants should be preferred because they are more adaptable to local climate, which may lower maintenance cost, and they are far more valuable in creating urban wildlife habitats than non-native species by providing favorable food and shelter for wildlife. More green spaces mean less impervious area, less pollution, cleaner air and water, and a healthier environment, giving residents in the city more natural capital and the ability to enjoy more complete ecological services from the urban ecosystem in which they live. To maximize the benefits, it requires deliberate planning so that green projects will form a green network that intertwines with and extends into existing greenways. One suggestion for this purpose is to grow genetically proper native trees, shrubs, and forbs in urban nurseries for use in the green infrastructure program. This plant material could be grown with local trained labor and result in a less costly product, enabling more planting for the money available.

Community Sustainability. Green infrastructure planning, especially green street planning and design, provides opportunities to reconfigure some city streets where more pedestrian friendly streets may be created. Studies have indicated that green streets are, with more plantings, even though likely narrower, often safer for both cars and pedestrians due to reduced speed from vehicles. Onondaga County and the City of Syracuse have incorporated designated bike lane planning into the green infrastructure planning and design process wherever applicable, trying to create an environment that relies less on automobiles. Businesses may be attracted to the local neighborhoods when there is no need for cars or parking lots.

The vacant lot program described above contributes to making sustainable communities in another way. Besides the function of managing stormwater, those vacant lots can also accommodate urban orchards, vegetable gardens, the growth of bio-mass, and flower gardens that will produce fresh food, fiber, and beauty throughout the community. The plan is to do this as much as possible with local neighborhood people either employed by a newly formed entrepreneurial green infrastructure company or by existing not-for-profits engaged in the effort to improve the quality of life of their constituents. All the above improvements to the community will encourage people to walk and work outside, which prompts more surveillance on the street, in turn, making the community safer.

The potential of green infrastructure to be at the forefront in creating sustainable cities is tremendous, but institutional roadblocks must still be overcome for communities to realize this potential. Human brains working together can create new and restored environments that foster the better aspects of human nature while decreasing crime and anti-social behavior. For this to come to fruition, however, problems and possibilities must be looked at in all their complexity and all stakeholders and all professional disciplines must work together to improve the quality of life for all our residents and visitors.

In closing, all efforts being taken for Onondaga Lake cleanup, which involve Onondaga County and City of Syracuse communities as well as administrative and technical support from outside, have the same final goal: to bring Onondaga Lake back to life. Recent monitoring results have indicated that the water quality of Onondaga Lake has been dramatically improved, as has its overall ecological condition. While the lake cleanup activities continue, Onondaga Lake is close to becoming swimmable, and the number of fish species has increased from 9-12 in the

1970s to today’s 66 species found. Onondaga County’s lake improvement efforts, initiated by the ACJ as the County’s legal obligation, have evolved and become a successful story of applying greener, more sustainable approaches to address urban water quality issues. More importantly, the Save The Rain green infrastructure program in Syracuse and Onondaga County is moving beyond its legal compliance goal, and this has further pushed the envelope towards improving the quality of life for local communities in general.

The Urban Forest Is Broken: How We Can Enhance 1,000,000 Tree Initiatives to Meet Stormwater Goals

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Abstract

Mature trees contribute significantly to urban stormwater management and provide many other benefits. This presentation will explain the different processes by which trees provide stormwater management, as well as the magnitude of stormwater benefits possible with trees, supported by the latest research and case studies.

A growing awareness of the multiple benefits of large trees has many cities developing initiatives to plant large numbers of trees. New York City, for example, aims to plant one million trees over the next decade. But without paying attention to how these trees are planted, the trees will never grow large enough to produce anywhere near the level of ecological services they are ultimately capable of providing or meet the expectations of those proposing the tree planting programs.

Studies have found that trees surrounded by pavement in urban downtown centers only live for an average of 13 years, a mere fraction of their much longer lifespan under natural conditions. The most significant problem urban trees face is the inadequate volume of soil useable for root growth. Research has shown that trees need approximately 2 cubic feet of soil volume for every 1 square foot of canopy area. Most urban trees, confined to a 4’ x 4’ x 4’ tree pit hole, have less than 1/10th the rooting volume they need to grow large. Additionally, the hunt for super-trees that can tolerate the stress of urban environments has resulted in low species diversity, rendering urban forests very susceptible to catastrophic losses such as those from Dutch Elm Disease and Emerald Ash Borer.

This presentation will provide holistic policy, design, and management recommendations for how to create healthy, resilient urban forests that will allow trees to grow large enough to provide significant stormwater volume, quality and rate benefits.

Introduction

Mature trees can contribute significantly to urban stormwater management and also provide many other benefits, such as cleaner air and water, urban heat island effect reduction, enhanced property values, and more. Aware of the multiple benefits of large trees, many cities are developing initiatives to plant large numbers of trees. New York City, for example, aims to plant one million trees over the next decade. Yet many of the large scale tree planting initiatives that are taking place in major cities nationwide fail to address the planting conditions needed to make mature tree growth in the built environment a reality, dooming them to failure.

According to the US Forest Service, a large tree with a trunk diameter 10 times larger than a small tree (76.2 cm vs. 7.62 cm, i.e., 30 inch vs. 3 inch diameter at breast height) produces 60-70 times the ecological services (McPherson et al, 1994)! These benefits are especially needed in large cities, where the average lifespan of a tree is estimated to be only 13 years, not long enough to produce anywhere near the level of ecological services they are ultimately capable of providing. Our current urban forest model is broken, and we have much to gain by fixing it.

Stormwater Benefits of Trees

Stormwater Quantity and Rate Control Benefits of Trees. Trees can provide significant stormwater quantity and rate control benefits through the following processes:

- Soil storage
- Interception
- Evapotranspiration

If properly designed, installed, and maintained, their capacity to manage stormwater on-site, without requiring much open space, is particularly valuable for urban settings, where vast stretches of impervious surfaces often make flooding, non-point source pollution, and CSO overflows a risk even during small rainfall events.

Soil Storage. Soil stores rain water during and after a storm, making it available for tree growth. Directing stormwater from impervious surfaces to tree soil can provide a significant amount of stormwater storage. A tree with a 25' diameter needs 1000 cubic feet of soil to thrive. If this soil has 20% water storage capacity (a conservative estimate since some bioretention soils can hold up to 40% water), it can hold the one inch 24 hour storm event from 2,400 square feet of impervious surface. So the soil volume needed to grow a large tree can hold the 1 inch storm event from impervious surface area significantly greater than just the area under the tree canopy.

Stormwater calculations for trees used for bioretention typically account only for soil storage, not for interception and evapotranspiration.

Interception. Interception is the amount of rainfall temporarily held on tree leaves and stem surfaces. This rain then drips from leaf surfaces and flows down the stem surface to the ground or evaporates.

Interception is not typically included in stormwater calculations but can nonetheless provide additional stormwater benefits beyond stormwater storage in the soil.

The volume of rain intercepted depends on the duration and rate of the rainfall event, tree architecture (e.g. leaf and stem surface area, roughness, visual density of the crown, tree size, and foliation period), and other meteorological factors.

Since larger trees have more leaves to intercept rain, they intercept significantly more rain than small trees, with interception increasing at a faster rate than tree age. For example, a model of a hackberry tree in the Midwest estimates that interception will increase as follows with tree age:

- a 5 year old hackberry intercepts 0.5 m^3 (133 GAL) rainfall per year
- a 20 year old hackberry intercepts 5.3 m^3 (1,394 GAL) rainfall per year
- a 40 year old hackberry intercepts 20.4 m^3 (5,387 GAL) rainfall per year

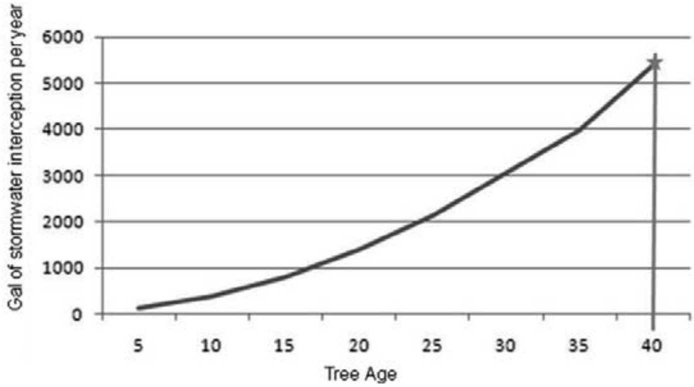

Figure 1: Stormwater interception by hackberry trees versus age of tree (adapted from McPherson et al, 2006)

Evapotranspiration. Evapotranspiration (ET) is the sum of water evaporated from soil and plant surfaces and the water lost as a result of transpiration, a process in which trees absorb water through their roots and transfer it up to the leaves, where it evaporates into the environment through leaf pore transpiration. Evapotranspiration continues to reduce stormwater volume stored in the soil long after a rainfall event ends.

Transpiration rate is influenced by factors such as tree species, size, soil moisture, increasing sunlight (duration and intensity), air temperature, wind speed and decreasing relative humidity.

Potential evapotranspiration (PET) exceeds precipitation during the growing season in much of the US. Even tree transpiration can exceed precipitation, especially where it is sustained by irrigation (Grimmond and Oke 1999).

Transpiration uses heat from the air to change the water in the vegetation into water vapor, so in addition to providing stormwater benefits, transpiration also decreases ambient air temperature and reduces the urban heat island effect. Trees in Davis, California, parking lots, for example, reduced asphalt temperatures by as much as 36° F, and car interior temperatures by over 47° F (Scott et al 1999).

Stormwater Quality Benefits of Trees. The soil, trees, and microbes in a bioretention system with trees work together as a system to improve water quality of stormwater that is filtered through the tree's soil. Some pollutants are held or filtered by soil, others are taken up or transformed by plants or microbes, and still others are first held by soil and then taken up by vegetation or degraded by bacteria, "recharging" the soil's sorption capacity in between rain events. Table 1 below summarizes some of the main bioretention pollutant cleansing mechanisms.

Table 1: Summary of Bioretention Water Quality Cleansing Mechanisms for Common Stormwater Pollutants

Pollutant	**Bioretention Cleansing Mechanism**
TSS	Sedimentation and filtration (e.g. Davis et al 2009)
Metals	Filtration of particulate metals, sorption of dissolved metals onto mulch layer (e.g. Davis et al, 2009), plant uptake (e.g. Toronto and Region Conservation, 2009)
Nitrogen	Sorption; uptake by microbes and plant material, uptake into recalcitrant soil organic matter (e.g. Henderson, 2008)
Phosphorus	Sorption, precipitation, plant uptake, uptake into recalcitrant soil organic matter (e.g. Henderson, 2008)
Pathogens	Filtration, UV light, competition for limited nutrients, predation by protozoa and bacterial predators (e.g. Zhang et al 2010)
Hydrocarbons	Filtration and sorption to organic matter and humic acids, then degraded by soil microbes (e.g. Hong et al 2006)

Several recent literature reviews of lab and field studies of bioretention pollutant removal have concluded that bioretention systems have the potential to be one of the most effective BMP's for pollutant removal. High concentration and load reductions are consistently found for suspended solids, metals, polycyclic aromatic hydrocarbons (PAH), and other organic compounds. Nutrient (dissolved nitrogen and phosphorus) removal has been more variable. Healthy vegetation has been found to be especially crucial for removal of dissolved nitrogen and phosphorus. Several studies that have compared vegetated media to unvegetated media have found that the presence of vegetation substantially improves TP and TN retention, as vegetated media is much more effective than unvegetated media at removing PO4 from solution and preventing NO3 leaching from media (e.g. Henderson et al 2007, Lucas and Greenway 2007a, 2007b, 2008, May et al 2006). Not only has vegetation been shown to significantly improve nutrient removal, trees also seem to benefit from the nutrients in the stormwater, as a study that compared growth of trees irrigated with stormwater to trees irrigation with tapwater found that the trees irrigated with stormwater had greater height growth and root density compared with those irrigated with tap water (May et al 2006).

For a summary of research on bioretention and water quality, see, for example, Davis et al 2010, Davis et al 2009, Table 1.1 in Henderson 2008, and the BMP database at http://www.bmpdatabase.org/.

For more on how vegetation improves bioretention nutrient removal, see, for example, Henderson et al 2007, Lucas and Greenway 2007a, 2007b, 2008, May et al 2006.

Strategies to Fix the Broken Urban Forest Model

Problems with Current Urban Forest Model. Studies have found that trees surrounded by pavement in urban downtown centers only live for an average of 13 years (Skiera and Moll, 1992), a very small fraction of their much longer lifespan under natural conditions. The most significant problem urban trees face is the inadequate quantity of soil useable for root growth. A large volume of uncompacted soil, with adequate drainage, aeration, and fertility, is the most significant key to the healthy growth of large trees. Research has shown that trees need 2 cubic feet of soil volume for every 1 square foot of canopy area (Lindsey and Bassuk, 1991). Most urban trees, confined to a 122 cm x 122 cm x 122 cm (4’ x 4’ x 4’) tree pit hole, have less than 1/10th the rooting volume they need to thrive. These trees – no matter how many of them are planted – never receive the resources they require to become ecological and environmental assets to their communities.

Additionally, very few tree species can survive in typical urban tree pits, so only a few species of “supertrees” are typically grown. Limited species diversity in turn reduces the resilience of the urban forest and renders it very susceptible to outbreaks like, for example, Dutch Elm Disease.

Proposed New Urban Forest Model. Recognizing the need to fix the broken urban tree model by starting with changes to how we plant street trees, several cities in the US and throughout the world have recently developed regulations requiring minimum soil volumes. Most target about 56,630 cm^3 (2 cubic feet) of uncompacted soil volume per 0.1 m^2 (1 square foot) of tree canopy. The presentation will show example codes from Emeryville, California (2008), Toronto, Canada; and Charlotte, North Carolina (1985).

Using innovative techniques, such as suspended pavement, to extend rooting volume under HS-20 load bearing surfaces and create favorable tree growing conditions in urban areas, enables trees to grow to their mature size AND provide the stormwater and ecological benefits commensurate with mature trees. In addition to providing the tree the rooting volume it needs to grow to maturity, the rooting volume also stores, filters, and detains significant stormwater volumes.

In areas that do not have enough open space to grow large trees, techniques like suspended pavement can be used to extend rooting volume under HS-20 load bearing surfaces and create favorable conditions to grow large trees in urban areas. While suspended pavement has been built in several different ways, all suspended pavement is held slightly above the soil by a structure that "suspends" the pavement above the soil so that the soil is protected from the weight of the pavement and the compaction generated from its traffic.

Using Silva Cells, modular structures designed to support pavement to protect soil inside the cells from compaction is one example of a technique to support pavement loads and protect soil inside the cells from compaction (see Figure 2).

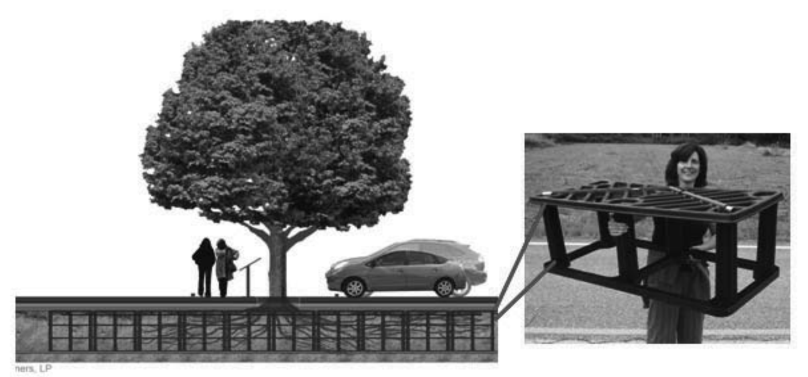

Figure 2: Silva Cell Illustration

The oldest installations of suspended pavement of which we are aware were installed in 1985 in Bethesda, Maryland, and in Charlotte, North Carolina. In both cities, the trees have performed significantly better than the average urban tree that only lives to be 13 years old.
In Bethesda, Maryland:

- Average tree height was 12.2 to 13.4 m (40 to 44 feet)

- Average diameter at breast height (DBH) was 356 to 508 mm (14 to 20 inches)
- Average soil volume was 17 m^3 (600 cubic feet) (not counting soil sharing)

For the trees in suspended pavement in Charlotte, North Carolina:

- Average soil volume was 17 m^3 (700 cubic feet) (not counting soil sharing)
- 167 out of 170 trees planted (98%) are still alive 26 years after planting.
- Average height is 13.4 m (44 feet)
- Average DBH is 0.4 m (16 inches)

Figure 3. Trees in suspended pavement in Charlotte, North Carolina

A study by Bartlett Tree Research Laboratories has been comparing tree growth in natural soil under suspended pavement compared to growth of trees grown using other ways to prevent rooting volume compaction under pavements: stalite soil, and gravel soil (ie structural soil), as well as to trees grown in compacted soil. Each tree was provided 5.7 m^3 (200 cubic feet) of rooting space. As of 2010, the 6th year of the study, Elm growth was best in the suspended pavement with natural soil (see Figures 4 and 5).

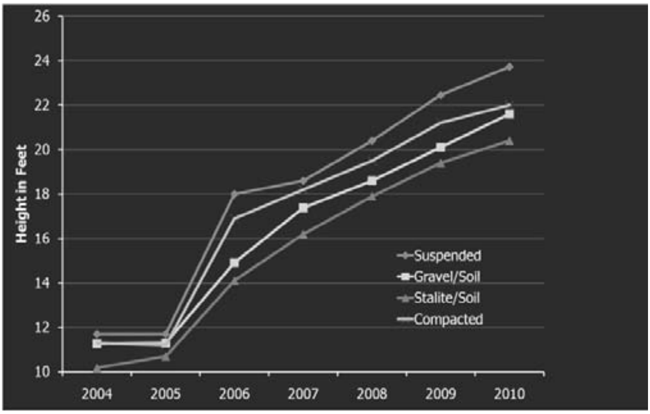

Figure 4. Results of 6 years of tree height measurements of trees grown in suspended pavement vs. gravel/soil vs stalite/soil vs. compacted soil (E. Thomas Smiley, Ph.D., Bartlett Tree Research Lab, Charlotte North Carolina, Adjunct Professor Clemson University, unpublished data)

Figure 5. Comparison of trees grown in suspended pavement, compacted soil, stalite/soil, and gravel/soil 6 years after planting (Image courtesy of Thomas Smiley).

Once trees are provided adequate volumes of loam soil, more species can thrive in urban areas, and higher species diversity can realistically be targeted. Increased species diversity, in turn, renders the urban forest more resilient and less susceptible to insect and disease outbreaks.

While planting urban trees with adequate uncompacted soil volumes, such as, for example, with suspended pavement, is more expensive up front, a lifecycle cost analysis for a typical example scenario in Minneapolis MN, showed that over a 50 year study period, planting a tree with suspended pavement for stormwater treatment has significantly lower lifecycle costs than a conventional urban tree. The study compared:

(1) An urban tree, with pavement suspended over adequate uncompacted soil volume, which:
  - Costs more to install than a traditional urban tree with insufficient uncompacted soil volume
  - Has an estimated lifespan of 50+ years
  - Lives to be a mature tree that provides significant ecological and financial benefits, and

(2) An urban tree with insufficient uncompacted soil volume, which:
  - Costs much less to install than the tree with suspended pavement
  - Has an estimated lifespan of 13 years, so it has to be replaced 3 times during the 50 year lifespan of the tree with suspended pavement
  - Dies before it grows large enough to provide significant ecological and financial benefits

For a 50 year study period, the analysis indicated:

(1) *Estimated BENEFITS* outweigh estimated *COSTS* by $25,427.22 for the Tree With Suspended Pavement, designed for Stormwater Management: estimated $2.56 investment return for every $1 invested
(2) *Estimated COSTS* outweigh estimated *BENEFITS* by $3,094.29 for the Tree With Insufficient Uncompacted Soil Volume: estimated $0.47 investment return for every $1 invested. (The Kestrel Design Group, 2011).

Case Studies

A number of case studies are presented to show the magnitude of stormwater treatment possible with urban trees with bioretention soil under suspended pavement.

Minneapolis Case Study. In downtown Minneapolis, 48 blocks of trees with uncompacted bioretention soil in suspended pavement were installed as part of a transit-way streetscape renovation in 2009.

The trees and structural cells in this project collect runoff from the sidewalks along 2 of Minneapolis' main downtown streets through pervious pavers that drain into the underlying structural cells. One of the structural cell groups also collects roof runoff from adjacent buildings.

While the amount of runoff treated per tree varies from block to block and from tree to tree, on average, each tree pit collects runoff from about a 27.9 m^2 (300 square foot) watershed. With 167 trees, this adds up to an estimated 0.5 hectares (50,118 s.f., or 1.15 acres) of sidewalk runoff captured. Each tree has on average 16.65 m^3 (588 cubic feet) of soil with an estimated 20% water storage capacity, so each tree provides about 3.341 m^3 (118 cubic feet) of stormwater storage. A 2.54 cm (1 inch) rainfall event on the average 27.9 m^2 (300 s.f.) watershed produces 0.71 m^3 (25 cubic feet) of runoff. To fill up the average 3.341 m^3 (118 cf) of stormwater storage per tree from a 27.9 m^2 (300 s.f.) watershed would take a 12.7 cm (5 inch) storm event. The soil in the structural cells therefore has enough capacity to capture runoff from a 2.54 cm (1 inch) rain event from 5 times as much impervious surface as it currently captures. In other words, the soil in the structural cells has capacity to capture 2.54 cm (1 inch) of rain from 2.33 hectare (5.75 acres) of impervious surface.

The City of Minneapolis is reserving this extra soil stormwater holding and infiltration capacity for future use.

Toronto Case Study. The largest project to date using trees with suspended pavement for stormwater management is Waterfront Toronto. To date, 1300 trees have been installed as part of phase 1. When complete, the project will include a total of 16,800 trees, which will manage the 90% storm for 849.8 hectares (2100 acres) of ultra urban re-development!

Conclusion

The new model for urban trees and stormwater management pioneered in Minneapolis and Toronto provides an alternative that is ***effective, resilient, and cost effective***. These examples show that it is possible to plant large numbers of urban trees with soil volumes adequate for the trees to live to maturity and provide significant ecological services. They demonstrate an integrated approach to stormwater management, that not only provides significant stormwater services, but also cleans urban air, reduces the urban heat island effect, and beautifies the city.

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Green Stormwater Retrofits: Objectives and Costing

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Abstract

With the issuance by the State of Maryland of its 2010 stormwater permit, Montgomery County (Montgomery) was required to retrofit 20% of its older, untreated or poorly-treated impervious surfaces by 2015. In January 2012, the County released its final strategy for meeting this retrofit goal. The strategy includes using Environmental Site Design (ESD), or green infrastructure, for 18% of its retrofit obligations, with the bulk of the remainder to be achieved through stormwater pond retrofits. Unit costs for some innovative green retrofits are lower than others, and different mixes of green practices can be applied to different land cover categories. Using alternative mixes of these innovative green practices and independent local cost data, a back-of-the-envelope analysis indicates that it may be possible – and affordable – to apply green stormwater retrofit practices to more than half of the Anacostia Watershed's targeted 1421 impervious acres in Montgomery County. A new unit cost metric, dollars per Acre-inch of runoff reduced, is introduced. Examination of an alternative green retrofit scenario for Montgomery's Anacostia watershed area suggests that this approach merits further in-depth consideration, both for Montgomery County and for other stormwater permittees facing similar imperviousness restoration mandates.

Montgomery County's Stormwater Program, the Restoration of the Anacostia River and the Chesapeake Bay

The issuance of municipal stormwater permits under the federal Clean Water Act in the late 1990s, combined with the advent of green infrastructure technologies, provides an unprecedented opportunity for making our cities, towns, and suburbs greener, cleaner, and more sustainable. Montgomery County in Maryland is a prime example of a municipality that is investing in green stormwater retrofits and seeing their potential to yield broader benefits. This County's residents want and need clean water, restored streams and leafy communities. Montgomery

County is complying with its Municipal Separate Storm Sewer System permit ("MS-4 Permit") under the federal Clean Water Act in a way that increasingly responds to this need for greener neighborhoods. This informal case study of the potential for green stormwater retrofits in the County's Anacostia Watershed portion suggests that a broader toolbox of vegetated green retrofit techniques is available at lower costs than are now assumed. This expanded green toolbox deserves more in-depth consideration by Montgomery County and other municipal stormwater permittees.

Montgomery County's total land area is about 500 square miles, or about 325,000 acres; of which 11%, or 36,000 acres are impervious. While about one-third of the County is preserved as rural farms and forests in the Agricultural Reserve, and in parklands, the urbanizing pressures on the other two-thirds of the County are severe. These pressures, including increased imperviousness, have reduced the biodiversity and damaged the physical habitat of the County's streams.

Spurred on by several state and federal regulatory mandates, Montgomery County has developed an ambitious program for mitigating the impacts of urbanization. Pursuant to Montgomery's 2010-2015 MS-4 Permit, the County is required to restore 20%, or 4,292 acres, of untreated impervious surface. This retrofit obligation is part of a long-term strategy to meet Montgomery County's total maximum daily load ("TMDL") targets for nutrient and sediment loading established under the Watershed Implementation Plan for the Chesapeake Bay (Bay WIP), as well as the TMDLs established for local watersheds, including the Anacostia TMDLs for sediment, bacteria, trash and other pollutants. Table 1 shows the pollution and volume reduction targets for Montgomery County overall, and for the portion of the Anacostia Watershed in the County (Montgomery County 2012b, Table 4.2, p. 28; Table 4.6, p. 36).

Table 1. Montgomery County Pollutant and Volume Reduction Targets for the Chesapeake Baywide and Anacostia TMDLs – Stormwater permit mandates

Objective	Baywide TMDL - Mont. Co. portion 2015	Baywide TMDL - Mont. Co. portion 2020	Anacostia TMDL/ MS-4 Targets 2015	Anacostia TMDL – MS-4 Targets 2020
TP	17%	34%	27%	77%
TN	18%	36%	25%	68%
TSS	23%	54%	47%	100%
Trash	18%*	33%*	41%	89%
Bacteria	11%*	20%*	21%	46%
Flow Reduction	N/A	19%	N/A	34%

* Trash and bacteria targets are from Montgomery's 2010-2015 MS-4 Permit plan and are not Bay-wide. Flow Reduction targets in the MCCIS do not have a specific deadline.

The Anacostia is one of the most highly urbanized and degraded watersheds in Montgomery County, with 18% impervious cover. The County's portion of the Anacostia River watershed comprises about 61 square miles, roughly one-third of the watershed's total area. Because of the Anacostia watershed's high profile and the degree of degradation, of the 4,292 acres the County is required to restore under the current MS-4 Permit, the County has targeted 1,421 acres in the Anacostia watershed. In developing its retrofitting plan for the Anacostia, the County drew heavily from the Anacostia Restoration Plan, which identified about 200 green stormwater retrofits in Montgomery's portion of the Anacostia (Anacostia Watershed Restoration Partnership 2010 a).

Montgomery's Stormwater Retrofit Strategy

The County's comprehensive strategy to comply with the MS4 Permit retrofit obligation is set forth in the 2012 Montgomery County Countywide Coordinated Implementation Strategy ("MCCIS") (Montgomery County 2012b). The MCCIS is based on Watershed Implementation Plans (WIPs) that were developed for each watershed within the County. As set forth in the MCCIS, and pursuant to the MS-4 permit, the County plans to meet its restoration requirement through a mix of 3 types of practices: 1) traditional structural (pond) retrofits, 2) Environmental Site Design practices ("ESD"), and 3) stream restoration projects. ESD is a term specific to Maryland's stormwater regulations, but it is more or less synonymous with Low Impact Development, or Green Infrastructure (Montgomery County 2012b). The MS4 Permit leaves the relative proportion of the types of practices to be utilized in meeting the retrofit obligation up to the permittee.

In the MCCIS the County proposes to use ESD practices to address 18% of the required impervious acres to be restored (Montgomery County 2012b, Table 4.2 p. 28). Recent public statements by County officials indicated that this number has since been lowered to 12 to 15% (Shofar 2012). Based on a review of Montgomery's MS-4 planning documents, and discussions with County staff, both cost and site-feasibility played a role in the selection of restoration methods, although increased cost projections for certain practices appears to have played the primary role in the County's reduction of ESD retrofits from 18% to between 12 and 15% of the total retrofit obligation.

Multiple Benefits of Green ESD Practices

ESD retrofits are superior to stormwater ponds and other detention practices because they not only reduce pollutant loadings, but because they reduce rather than merely detain stormwater volumes, thereby helping to restore natural hydrologic flow and contributing to stream biological recovery (Table 2.)

Table 2. Water Resource Objectives of Restoration Methods

Method	**Objective** Reduce Loadings	Reduce Runoff	Restore Biology
Pond Retrofit	X	N/A	N/A
ESD	X	X	X
Stream Restoration	X	N/A	X

According to Montgomery County's own MS-4 documents, ESD practices are not only more effective at reducing nutrient and sediment loading, but they have far superior volume reduction capability compared with detention ponds (Table 3). The percentage removal figures in Table 3 are from the Montgomery County Department of Environmental Protection (DEP) consultants' MS-4 implementation plan guidance document (Schueler 2011). Moreover, in addition to better water quality protection, there is growing recognition that ESD approaches provide multiple benefits that detention ponds don't provide, such as ancillary environmental, economic, and social benefits, including carbon sequestration, greenhouse gas emissions reduction, urban heat island mitigation, ground water recharge, improved air quality, increased property values, habitat creation and improved livability (CNT 2010, ECONorthwest 2011).

Table 3. Planned ESD Retrofit Toolbox for Montgomery County

Retrofit Practices	**Performance Capability (Montgomery County 2011, pp. B21-B23, Tables B.17-B19.)**			
	Runoff Reduction (%)+	**TSS removal (%)**	**TN removal (%)**	**TP removal (%)**
Bioretention (ESD)	60	90++	77	72
Permeable Pavement (ESD)	60	n/a	70	70
Cisterns (ESD)	52.5	n/a	52.5	52.5
Green Roofs (ESD)	52.5	n/a	52.5	52.5
Ponds (effective BMPs)	10	80	40	50

+ Runoff Reduction is defined here as "percent annual reduction in post development runoff volume for storms." (Table B.17, Footnote 1; Table B.18).

++ ESD practices (composited) were assigned an average TSS removal rate of 90%.

Volume Reduction Vs. Detention

When compared with ESD practices, detention ponds cannot significantly reduce total stormwater volumes discharged per storm event or per year; nor can they reduce the frequency of high-volume, high-impact storm events or the duration of potentially erosive storm flows in streams. Detention ponds create a trade-off in which the peak flow rate of stormwater is reduced when compared with an urbanized area with no controls, but the duration of higher-volume stormwater discharges is extended (Figure 1). An unintended consequence of detention ponds is the so-called multiple bathtub effect: when a subwatershed has multiple detention ponds, during a moderate or large storm, the discharges can combine to create an erosive flood condition in the mainstem.

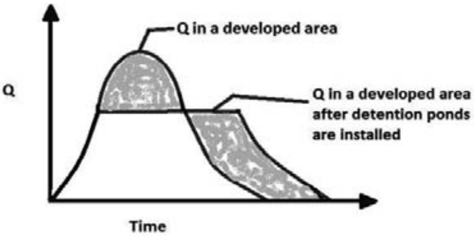

Figure 1. Detention basins effectively remove the top part of the hydrograph, but extend the duration of flow.

The National Research Council Stormwater Committee, in its 2008 report, highlighted the need for attention to the full spectrum of hydrologic flows, not just peak shaving (National Research Council, 2008). The 2010 Anacostia Restoration Plan, published by the Anacostia Watershed Restoration Partnership (AWRP), also highlighted the importance of stormwater volume reduction (AWRP 2010b, p.55).

Determining the Green Share of the Retrofit Pie

Montgomery County recognizes the benefits of ESD and has made a substantial commitment to deploying ESD practices. Yet the total share of the retrofit pie, in terms of impervious acres to be served by ESD practices is considerably less than for traditional detention practices. There are several reasons that account for this. One key reason is that the County's unit-cost estimates for ESD practices, on a per-acre-treated basis, are dramatically higher than for pond retrofits and stream restoration. For ponds, the unit-cost estimate is roughly $12,000 per impervious acre, compared with about $200,000 per impervious acre served for ESD (Montgomery County 2011, Table B.21 p.B28). This means that retrofitting 12% to 15% of Montgomery's targeted 4,300 impervious acres with ESD practices could cost as much as $129 million, which is nearly half the County's entire restoration budget. This cost estimate makes it difficult to justify restoring more impervious acres with ESD practices, particularly if pollutant loading reduction is the sole metric. A second critical reason for the small percentage to be treated with ESD is that the County adopted a narrow range of ESD practices, which likely limited the number of potential sites with feasible ESD applications.

Attaining full watershed restoration requires that the County strive to reduce both stormwater volumes and pollutant loadings. Since ESD practices enable attainment of both of these objectives, while ponds and stream restoration can only primarily achieve pollutant reduction, a reframing of the MS-4 permit strategy is indicated. Is it in fact possible to incorporate more ESD into the County's retrofit strategy without exploding the budget? Preliminary research suggests that the answer is yes; there are emerging opportunities that can both lower the cost and increase the opportunity for utilizing ESD retrofits.

Approach to Identifying Lower-Cost ESD Retrofits

Lower-cost ESD retrofit practices and strategies fall into five categories: a) tree-based methods; b) tandem retrofits that are coupled to already-planned roadway or other capital projects; c) smaller "tweaks" to existing structures and sites, such as earth-berming and conservation landscaping on semi-bare, erosional slopes; d) practices that are placed lower in a subwatershed, thus enabling service to larger impervious drainage areas and reducing the unit cost, such as Regenerative Stormwater Conveyances and Trees in Dry Ponds; and e) low-cost or cost-saving changes in existing landscaping and maintenance practices, including expanding no-mow and no-leaf-blow zones in urban parks. Once these strategies are deployed, the list of potentially viable green ESD retrofit practices expands. Each ESD practice must be chosen for its suitability to a given site, and well-tailored to meet site-specific land-owners' and neighbors' needs. This study focused on categories (a) and (d): expanding the role of tree-based practices through an expanded toolbox and applying vegetated ESD practices lower in a watershed, so they can serve more impervious acres per ESD unit. Using this expanded toolbox and cost estimates derived through interviews and County data, we developed a cost-effective, alternative scenario for meeting the County's Anacostia Watershed retrofit and pollution load reduction goals while greatly increasing the number of acres served with ESD, thus expanding the green portion of the retrofit pie.

Back of the Envelope Analysis – Goals & Method

A Back-of-the-Envelope (BOTE) Analysis is a rough method of estimating and testing an alternative scenario in order to show what new and different approaches may be possible. Such an informal, rough scenario enables comparison with an official plan and invites further, more-detailed and formal analysis and modeling. In this case study, an alternative scenario for applying and costing a "mixed basket" of ESD practices is applied to the impervious acres in the Anacostia watershed within Montgomery County. The goals of the BOTE analysis were: 1) to support a larger role for green retrofits; 2) to stay within the County's five-year, $300 million retrofitting budget and within that, the Anacostia portion's $160 million budget; and 3) to highlight the efficacy and benefits of ESD practices.

Methodology

The County's Anacostia Watershed Implementation Plan (Montgomery 2012(a)) included a toolbox of 5 green retrofits; we added 7 additional green practices for a total potential "green toolbox" of 12 practices. Table 4 shows the new proposed mix of practices and their performance capabilities (for practices where there is a lack of published performance data, such as for some of the tree-based practices, performance capabilities were assumed based on best professional judgment). Montgomery's ESD toolbox is expanding every year; for instance in 2012 DEP is designing two Regenerative Stormwater Conveyances (RSCs, also called step-pool infiltration terraces), whereas in 2011 RSCs were not yet used by the DEP. Other examples of lower-cost green retrofits include: tree-based practices such as Trees in Dry Ponds, and non-structural tree plantings in parks and yards. Conservation Landscaping and Trees in Dry Ponds are examples of lower-cost vegetated practices that are nominally in the County's toolbox, but are either being used sparingly or are only in the demonstration phase. Though most of the proposed additional green retrofit practices tended to be lower cost, Trees in Suspended Pavement is in the upper cost range. The BOTE costing analysis used only the ten vegetated practices, omitting cisterns and permeable pavement. Bioretention (curb-contained) was subdivided into the green street and non-green-street (e.g. parking lot) varieties for costing purposes.

Unit cost data for the 10 vegetative ESD retrofit practices in the expanded toolbox were derived from a range of sources (Table 5). An effort was made to collect cost data specific to Montgomery County, in order to capture the impact of local market and regulatory conditions. Data sources for this study include: Montgomery County environmental and planning staff; public project managers; private developers, green infrastructure providers; site design firms and the County's published estimates (Schueler 2011). Roughly one-third, or about 10 people, responded to a stormwater practice cost and benefit query sent in September 2011 to 25 developers and public agency managers. Several respondents lacked cost data, and reported they are seeking such data themselves.

Staff for Montgomery DEP and the Center for Watershed Protection supplied most of the detailed costing data for our derivation of unit costs for tree-based practices, Rain Gardens and Conservation Landscaping. Table 5 reflects two sets of cost data. Column 1 shows County cost estimates for specific practices as set forth in the County's guidance document for impervious acreage retrofits (Schueler 2011). Column 2 shows cost data based on independent investigation. In many cases independent investigation was able to yield only one additional data point for a specific practice. It is worth noting, however, that some of these numbers are substantially lower than the County's estimates, suggesting that the cost data warrants additional research to verify average costs and to determine factors that contribute to broad variability. Significantly, both County and independently-collected data support the conclusion that the proposed new vegetative practices cost on average significantly less per acre treated than the 5 ESD practices in the mix currently employed by the County.

For the purposes of our BOTE analysis we have developed two alternative scenarios: a conservative alternative scenario ("conservative scenario") and a best-case alternative scenario (the "best-case scenario"). The conservative scenario uses the higher-cost cost data developed by the County, whereas the best-case scenario uses the independently collected data. Where there is only one source of data for a specific practice, that data is used in both scenarios. Both of our alternative scenarios use an expanded list of vegetation and tree-based ESD practices; this expanded mix when combined with the two different sets of unit costs, provides alternative total cost estimates for ESD retrofits for a range of land cover categories.

Table 4. Proposed Expanded ESD Retrofit Toolbox for Montgomery County

Planned ESD Retrofit Practices	**Performance capability (Schueler 2011). Implementation Plan Guidance Memo, P. B21, Table B.17.**			
	Runoff Reduction (%)+	**TSS removal (%)**	**TN removal (%)**	**TP removal (%)**
Bioretention (curb-contained)	60	90	77	72
*Permeable Pavement	60	n/a	70	70
Rain Gardens	60	n/a	60 (assumed)	60 (assumed)
*Cisterns	52.5	n/a	52.5	52.5
Green Roofs	52.5	n/a	52.5	52.5
Proposed Additional ESD Practices – Alternate Scenario				
Trees in Dry Ponds	60	90	65	65
Trees in Single-Family Lots/ Res. Rights-of-Way (assumed)	60	90	65	65
Regenerative Stormwater Conveyance	60	90	65	65
Conservation Landscaping (assumed)	60	90	77	72
Riparian Reforestation and Deer Management++	60	50	25	50
Bioswales (curbless)	50	90	65	65
Trees in Suspended Pavement (assumed)	50	50	50	50

* Not included in Alternate Scenario / Analysis.

\+ Runoff Reduction is defined here as "percent annual reduction in post development runoff volume for storms." (Table B.17, Footnote 1; Table B.18).

++ Montgomery County 2011, Table B.20, p. B25.

Table 5. Vegetated ESD Retrofit Practices Unit Costs

ESD Retrofit Practices	Unit Cost – $/Imp. Acre – Conservative Scenario	Unit Cost – $/Imp. Acre – Best-Case Scenario	Sources #Data Pts.
Tree Planting – parks and yards	20,000	8,700	2
Tree Planting - Dry Ponds	57,000	14,618	2
Riparian Reforestation	20,000	13,289	2
Conservation Landscaping	298,000	80,625	2
Regenerative Stormwater Conveyance	35,000	35,000	2
Curb-Contained Bioretention	200,000	200,000	1
Curb-Contained Bioretention For Green Street projects	350,000	350,000	1
Rain Gardens	298,000	200,000	2
Trees - Suspended Pavement	169,400	169,400	1
Green Roofs	817,000	501,000	2
Bioswale (without curbs)	137,000	137,000	1

ESD Sets of Practices Tailored to a Set of Land Cover Categories.

In developing the plan for the Anacostia Watershed, the County broke the watershed down into a number of "land cover categories" (*e.g.*, County Roofs, Parking Lots, and Roads, etc.) and then identified appropriate retrofit strategies for each category, with estimates for acreage treated and cost (Montgomery County 2012a). Similarly, for the purpose of this analysis, a mix of ESD practices was tailored to each land cover category using the expanded toolbox, with total acreage and cost estimated accordingly.

Results

In order to illustrate the results of the BOTE analysis, we first look at its application to a specific land cover practice. Under the County's plan for the Anacostia, a combination of four ESD practices was allocated to retrofit the "County Roofs" land cover category. This combination called for an equal mix of green roofs, cisterns, permeable paving, and bioretention to capture roof runoff, yielding a $508,500 per impervious acre unit cost (Montgomery County, 2012a, Table 20). For our two alternative scenarios, best-case and conservative, we employed a different mix of 5 practices, including Conservation Landscaping and non-structural trees. In addition to lower per-unit cost estimates, the best-case scenario utilized a more optimistic mix of practices, emphasizing lower unit-cost practices over higher unit-cost practices, whereas the conservative scenario used a more balanced mix of practices. The per-acre unit costs for the best case and conservative scenarios to address public roofs are $168,469 and $270,800, respectively—a range of between one-third to one-half of the County's planned unit cost (Table 6). When applied to the 54 total impervious acres of public roofs in the Anacostia watershed portion of the County, the total cost of the ESD retrofits is $27.5 million in the County's planned scenario, but only $9.1 million in the best-case scenario and $14.6 million in our conservative scenario.

Table 6. ESD Practice Mix Applied to Public Roofs – Anacostia

ESD Practice & Cost per Impervious Acre (IA)	Fraction of Acres Served by Practice (Best-case Scenario)	Number of Impervious Acres
Curb-Contained Bioretention	0.4	21.6
Conservation Landscaping	0.25	13.5
Trees – Non-Structural	0.125	6.75
Green Roofs	0.1	5.4
Bioswales	0.125	6.75
Totals	1.0	54
VBest-case Scenario: $168,469/IA.	Total cost for 54 acres: $9,097,312	
Conservative Scenario (for Public Roofs): $270,800/IA.	Total cost for serving 54 Impervious Acres: $14,623,200	

Table 7 shows a comparison of the potential average unit-cost and total cost outcomes for retrofitting the total of 1,789 acres of impervious surface within the Anacostia Watershed across the full range of land cover types that were identified by the County as having ESD "restoration potential" in the Anacostia WIP (Montgomery County 2012(a)).

Expanding the ESD toolbox yields considerable cost saving—47% and 20% for the best-case scenario and the conservative scenario, respectively—over the planned scenario. More aggressive application of lower cost practices could yield even lower overall costs. Moreover, with the inclusion of new ESD practices in the toolbox, it is likely the available acreage with ESD restoration potential would increase, providing more opportunities for ESD application. Under the current strategy, the County is proposing to retrofit 1,421 acres within the Anacostia, of which 374 will be retrofitted with ESD. The total cost is projected to be $160 Million, with over $76 Million allocated to the ESD portion. Theoretically, using a best-case scenario, the county could use the expanded toolbox to retrofit all of the targeted 1,421 acres with ESD for $188 Million, only a 14% increase over the budget for the planned scenario that includes 74% non-ESD practices. Whether or not retrofitting 100% of the 1,421 acres with ESD is feasible, it seems probable that applying an expanded toolbox will permit the County to employ a considerably higher amount of green infrastructure than is currently proposed.

Table 7. Projected total ESD Costs for Restoring the Anacostia Watershed in Montgomery County – County projections compared with Alternative ESD Practice and Cost Scenarios.

Land Cover Type-Anacostia Watershed in Montgomery Co.	Projected Acres to be Restored	Projected Cost For County ESD-Montgomery County's Plan	Projected Cost Alternative ESD Scenario - Conservative	Projected Cost Alternative ESD Scenario - Best-Case
County Large Parking Lots	54	$17,000,000	$7,600,000	$6,000,000
County Roofs	54	$27,500,000	$14,600,000	$9,100,000
Schools	72	$35,000,000	$17,400,000	$19,400,000
Low-Density Res. Roads	344	$47,000,000	$47,400,000	$33,500,000
Other County Roads	552	$110,000,000	$147,000,000	$115,000,000
Res. Priority Neighborhoods	446	$133,000,000	$90,000,000	$31,000,000
Non-Res. Properties	269	$80,000,000	$40,000,000	$23,000,000
Total ESD	1791	$450,000,000	$364,000,000	$237,000,000
Unit-Cost per Impervious Acre		$251,256	$203,000	$132,328

Field reconnaissance to assess the opportunity for application for most of these practices in the Anacostia watershed was not possible within the scope of this BOTE study, with exceptions being field trips to a prominent dry pond cell with trees, and neighborhood assessments for residential retrofit practices in the Sligo Creek subwatershed in partnership with DEP. A field survey and pilot testing combined with a protocol is needed in order to verify assumptions about the feasibility of Trees in Dry Ponds (Center for Watershed Protection 2008).

On the Need for New Metrics to Measure Runoff Reduction

Given that ESD practices provide runoff reduction through infiltration, evapotranspiration, and/or harvesting for reuse, whereas other practices often either provide much less, or no runoff reduction, new metrics are needed to highlight and compare the runoff reduction cost effectiveness of each candidate practice. Since units-costs have become key factors in decisions on how to restore watersheds and with what mix of practices, new unit cost effectiveness metrics are crucial. A metric consisting of dollars per [impervious] Acre-Inch Reduced ($/AIR), may be useful in this capacity. It would enable comparison of ESD practices with conventional (storage and treatment) BMPs, and with stream channel restoration, on a more level playing field. Table 8. presents a mock-up example, for illustration purposes, of how a stormwater runoff reduction-costing metric would enable such comparisons. More work is needed to establish the technical basis for this metric, and to apply it to municipal and statewide watershed restoration plans, programs and budgets.

Table 8. Runoff Reduction Unit Cost Metric – Comparison of Retrofit Practices (Values are for illustration purposes only).

Practice	**\$/IA treated (thousands) (pollutant removal)**	**Fraction of 1” of runoff reduced (per 4-hr storm)**	**\$/Acre-Inch Reduced \$/AIR (thousands)**
Detention Ponds	\$12/IA	0.05	\$240/AIR
Curb-Contained Bioretention – Montgomery Co.	\$200/IA	0.9	\$222/AIR
Trees in Ponds	\$14/IA	1.0	\$14/AIR
Trees - non-structural	\$135/IA	0.9	\$150/AIR
Green Roofs	\$500/IA	0.9	\$555/AIR
Regenerative Stormwater Conveyance	\$35/IA	1.0	\$35/AIR

Conclusions and Recommendations

Through use of green infrastructure ESD restoration practices, Montgomery County’s stormwater permit program represents an investment in a higher quality of life for the entire County. Based on our analysis using a suite of ten vegetated ESD retrofit practices, and with further emphasis on low-cost ESD practices, it is possible that over half of Montgomery’s Anacostia Watershed impervious acres planned to be restored within the 2010-2015 permit term, (710 out of 1421 acres) could be served solely with ESD practices. This is possible within the County’s budget of \$160 million allocated to the Anacostia restoration for the total 1,421 total impervious acres slated to be restored during the 2010-2015 MS-4 permit term.

This alternative scenario deserves further serious consideration and feasibility testing through modeling, combined with field reconnaissance and expanded piloting and wider application of new practices. The seeking, piloting, and deploying of lower-cost ESD practices – such as those within the five categories we highlighted -- should be undertaken by Montgomery County and other MS-4 permittees in cooperation with the Maryland Department of the Environment.

By committing to reduce total stormwater volumes along with pollutant loadings as co-equal objectives in its stormwater retrofit strategy, Montgomery County would be able to more fully and effectively mimic pre-development hydrology in urbanized watersheds and thereby address and remedy a bigger range of stormwater impacts. Investments in well-designed ESD practices will yield multiple benefits both now and in the future. The benefits of this green infrastructure – ESD investment program include energy savings for public and private land owners who invest in green roofs and strategic tree plantings; higher property values in neighborhoods with more trees, and more walkable urban commercial districts, whose shade trees and beautiful landscaping features attract more shoppers and businesses.

Given the paucity of stormwater retrofit cost and benefit data, especially for green ESD practices, standard practices for public and private stormwater cost and benefit tracking and reporting need to be instituted. The Anacostia Watershed Restoration Partnership, ad-hoc subcommittee on Demonstration of Approaches is addressing this need, and is working on a method for stormwater cost and benefit tracking and reporting to be piloted in 2012 and 2013. Institution of new metrics, such as dollars per Acre-Inch Reduced, combined with stormwater cost and benefit tracking and reporting, and more aggressive deployment of green retrofits, will yield both more useful data and more effective and accelerated watershed restoration.

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Coupling Stormflow Attenuation with Gully and Trail Stabilization, Wissahickon Valley Park, Philadelphia

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Abstract

A variety of trail and channel stabilization and runoff reduction techniques were implemented within Philadelphia's Wissahickon Valley Park in Philadelphia. In addition to "conventional" bioinfiltration systems (not discussed here), the methods employed and described in some detail below include 1) the replacement of actively enlarging gullies below stormwater outfalls with stable "stepped infiltration swales"; 2) the obliteration and hydrologic restoration of steep, improperly routed trails; and 3) the installation of trailside microtopographic basins, "contour soakage trenches", designed to accept and infiltrate runoff from active trails and unpaved roadways. These best practices have wide application within semi-natural urban nature parks generally, many of which are seriously impaired hydrologically because of land use history, intensive human use today, and ongoing urban development along their periphery.

Background

Located in north Philadelphia, lower Wissahickon Creek flows through a deep gorge which has long been preserved within an 1,800-acre semi-natural urban nature reserve known as Wissahickon Valley Park (WVP). Although thickly forested, with many very large and old trees, both rapid runoff and erosion are prominent in many areas of this park. Gully erosion, along with channel erosion in steep tributary streams, has occurred because of stormwater drainage into the park from intensively developed areas located along its perimeter. Surface water erosion is occurring on unpaved utility roads within the park (which also serve as multi-use trails) and gullies have formed where stormwater, gathered from paved roads and parking areas, has been allowed to discharge onto unprotected slopes, which in WVP are mostly very steep.

WVP is also laced with 50 miles of dedicated trails, the majority of which are natural surface paths which are heavily utilized by pedestrians, bicyclists, and equestrians. Many paths are essentially unplanned social trails, and the combination of poor trail routing and heavy mountain bike and pedestrian traffic on the steepest trail segments has led to serious and widespread trail erosion within the park. Many fall-line trails (steep paths routed across slope contours), especially those which traverse natural hillside hollows, have developed into deep, water-concentrating gullies. All of these circumstances are speeding delivery of water and fine sediment to Wissahickon Creek, which has already been significantly impaired by excess sediment before it enters the park.

In order to counter these problems, the Philadelphia Parks and Recreation Department (PPRD), the Friends of the Wissahickon (FOW), and the Philadelphia Water Department (PWD) have joined forces and are all presently engaged in stream channel, gully, and trail rehabilitation projects throughout this historic park. As funds become available, unstable trails are being rebuilt, re-routed, or eliminated by the PPRD and FOW. The PWD's interest in the WVP stems from the fact that it manages and maintains many miles of water and sanitary sewer lines within park. Both gully erosion and stream erosion threaten this vital infrastructure, which for the most part is very old. The FOW, a nearly 90-year old conservation organization, has as its focus the preservation and enhancement of Wissahickon Valley Park in its entirety.

The simple stormwater management (SWM) and gully and trail stabilization measures described here have been designed and installed by Skelly and Loy, Inc. as part of a project sponsored by the FOW. The methods developed by Skelly and Loy are robust and are intended to cope with the relatively infrequent but very high-magnitude rainstorms which do most of the geomorphic work within WVP.

Selected Rehabilitation Techniques

Stepped Infiltration Swale. This application was devised and first employed by Skelly and Loy a few years ago in a gully stabilization project undertaken by PWD within a part of WVP known as Carpenter's Woods. Here (as in many other areas in the park), large permanent gullies have formed directly below stormwater outfalls where surface runoff collected in storm sewers from adjacent built-up areas was simply unleashed onto unprotected slopes. (These practices date from as much as 100 years ago, when there was little concern for the impacts of surface runoff to the park or its streams. The PWD is today actively engaged in reversing these conditions throughout the City.)

Such permanent "wet" gullies (i.e., gullies permanently subject to periodic stormflow discharges) below outfalls can be stabilized with check dams and by regrading and stabilizing oversteepened banks. However, this approach provides no

SWM function beyond somewhat lower flow depth and energy dissipation at the grade-control overfalls. In contrast, repairing these gullies using the stepped infiltration swale approach both eliminates erosion and provides runoff attenuation and enhanced infiltration opportunity.

This combined erosion control and SWM treatment consists of a series of stacked boulder sills which span the gully cross section. The "cells" between successive boulder sills are filled to near the top of the gully with smaller (but still very coarse) fragmental rock (Figure 1). Finally, the remaining banks adjacent to the filled gully are shaved back and planted to woody vegetation.

The boulder sills hold the smaller rock in place and create a naturalistic stair-step channel profile that will dissipate flow energy in the event of a rare storm capable of generating surface flow. In the case of all other storms, discharge from the outfall is routed immediately to the subsurface, where flow through this coarse rock "filter" both slows the flow and encourages infiltration into the floor of the former gully (Figure 1). The net effect of this is the elimination of fluvial erosion and reduced flow rate at the downstream end of the installation.

Larger stone is used to armor the "channel" floor just below the outfall and the sills (Figure 1). This is intended to protect against dislodgement of the smaller stone during major surface flow events (the entire surface of the cell can be paved with larger rock if necessary).

In the absence of effective (maintained) sediment traps at all contributing storm drains, fine sediment and floated debris will gradually accumulate in the voids within the coarse rock cells. (For example, large quantities of sand used for winter road traction are commonly discharged from stormwater outfalls in this area.) It is therefore anticipated that surface flow through the stepped swale will become more common over time as the structure ages. At that point, the gully will be fully erased and replaced by a rocky stepped-bed channel lined with vegetation. Although reduced, flow attenuation will still be provided by the stepped rocky bed and (ideally) closely encroaching woody vegetation.

Trail Closure and Slope Re-Naturalization. Overly steep, gullied trails are currently being closed and replaced by stable, well-drained and properly-aligned paths throughout the WVP. In this project, the closure and obliteration of the retired trail segments conforms to the following general sequence: 1) deep scarification and ridging of the existing trail tread; 2) backfill of the trail incision with clean, locally salvaged soil placed in well-compacted soil lifts; 3) creation of a hummocky, uneven micro-relief on the fill surface; 4) installation of a deep layer of shredded woody mulch overspread with larger branches and logs; and 5) the installation of woody forest understory plantings (Figure 2). Where feasible, closed trail segments should be filled to somewhat above the prevailing grade in order to re-create more or less even hillside contours after the fill has settled.

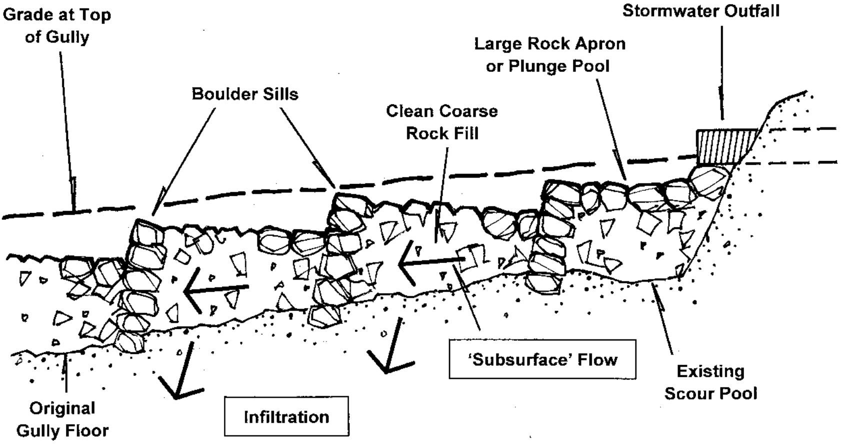

Figure 1. Typical profile along a stepped infiltration swale

To further promote long-term stability of the trail fill, buried woody debris dams, lodged in place within the trail cross section, are installed at irregular intervals along the filled trail profile (see Figure 2). These are intended to help buttress the fill; as they rot away, the ground surface will settle, creating microtopographic depressions mimicking natural root pits. Larger logs are also installed (preferentially along contours), which immediately create depression storage (and moist planting microsites) to prevent continuous surface runoff in the unlikely event of saturation-excess overland flow (Figure 2).

Taken together, all of these measures re-create a hydraulically rough and water-receptive surface which is intended to mimic the deep forest floor and "pit-and-mound" microtopography characteristic of pristine temperate forest landscapes (Hack and Goodlett, 1960; Hewlett, 2003). By restoring hillslope depression storage and enhanced infiltration opportunity, rapid and erosive surface runoff is replaced by infiltration and slow subsurface flow within the former trail footprint.

Contour Soakage Trench. One of the key methods of reducing runoff and erosion potential on active trails and unpaved roadways is to undulate the path or road surface with "rolling dips," which are minor inflections in the travelway. These divert surface runoff from the compacted traveled surface into "turnouts" which then typically discharge to the naturally vegetated hillside. Successive rolling dips reduce erosion potential by reducing slope length and removing surface flow from the travelway before it can gather speed.

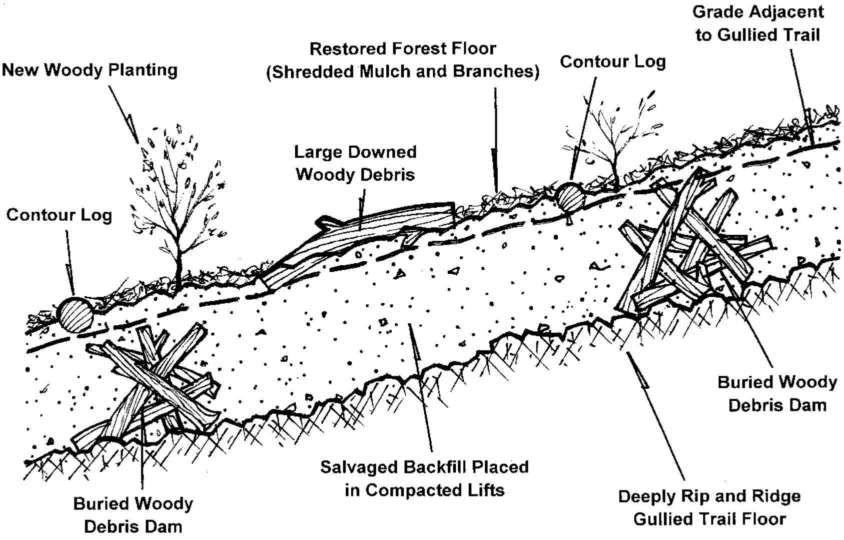

Figure 2. Typical longitudinal profile illustrating trail closure and re-naturalization techniques

When hillslopes are in a healthy condition hydrologically, the runoff diverted from the trail tread is quickly infiltrated and routed to shallow subsurface flow. Unfortunately, water-receptive hillside surfaces with the characteristics described above (deep forest floor, microtopographic complexity) are uncommon in WVP. Because of this, diverting surface runoff from trails or roadways onto such degraded slopes can simply move concentrated runoff and surface erosion from one location to another.

The installation of what we call “contour soakage trenches” is intended to very locally restore some measure of the highly water receptive conditions associated with a pristine forest floor. This allows water to be diverted from the traveled path without destabilizing the adjacent hillside. In order to illustrate the utility of this technique, these treatments were employed along both filled trail segments (as a “fail safe” measure) and along unpaved travelways which must remain in active use.

A contour soakage trench consists of a shallow hillside “trench” (linear depression) laid out along slope contours on one side of the trail. A dip in the trail tread is created so that trail runoff is quickly routed to the trench, whether directly or through a short turnout, which may or may not need to be armored. A constructed berm on the downslope side of the trench increases capacity and corresponds with the hump part of the rolling dip in the trail or roadway. A longitudinal profile through a typical contour soakage trench, taken a short distance away from and more or less parallel to the trail, is shown in Figure 3.

To construct a contour soakage trench, the shallow depression is excavated first, with this material then used to construct the low downslope berm (Figure 3). The bottom of the trench is ripped to promote infiltration and the entire disturbed area is then covered with a deep layer of woody mulch. Ideally, downed logs, limbs, and plantings are added to this treatment to further naturalize it.

All kinds of variations in this theme are possible. For example, large logs, shallowly embedded along the contour, can be used to create upslope depressions with little or no actual excavation. Existing natural trailside depressional areas, such as large old root pits, can also be exploited (and enlarged if necessary) for this purpose.

Conclusions

Forested hillsides in essentially undisturbed terrain have long been known to act as a veritable sponge, making them virtually immune to surface runoff and erosion (Hack and Goodlett, 1960; Hewlett, 2003). This is far less an effect of the trees themselves as it is related to conditions at ground level. Uncompacted forest soils with deep and extensive root systems, the high microtopographic roughness provided by fallen logs and the pits left by upturned trees, and a deep forest floor (duff and litter layer) are mainly responsible for runoff retardation, not the forest canopy.

Unlike natural forests, forest-covered urban parks have usually been subject to extensive surface alterations by people. Microtopography has often been largely erased and soils substantially altered by past logging or grazing. Changes to the sub-canopy ecosystem may have also left the forest floor and ground layer vegetation significantly depleted. To this can be added the effects of historically altered hillslope profiles (cuts and fills), the presence of roads and parking areas, and often excessively extensive (and usually poorly planned) trail systems. As a result of all of these effects, semi-natural urban parks can be surprisingly significant sources of both rapid surface runoff and the fine sediment generated by surface water erosion.

As demonstrated within WVP, a number of relatively simple techniques can be employed to minimize these impacts, thereby restoring the quality of such areas for all users and protecting downstream water quality. Stormwater-induced channels can be converted into rock-filled infiltration trenches to both prevent further gully enlargement and detain runoff. Stepped infiltration swales can be naturalized and disguised by adding large wood and plantings to their margins. Outside of channels, over-steep trails to be retired can be converted back to water receptive hillsides. Where trails and roadways must be retained, runoff can be diverted from these surfaces by installing rolling dips.

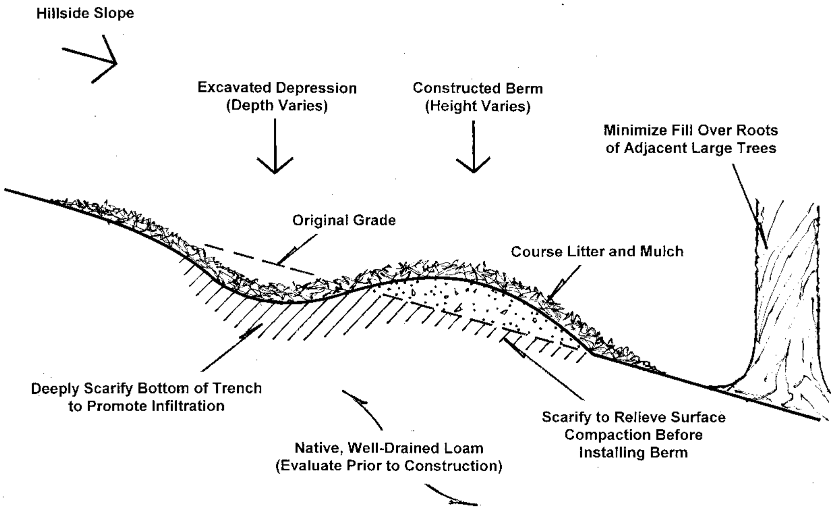

Figure 3. Hillside profile through a contour soakage trench

This runoff can then be routed into constructed contour soakage trenches which locally mimic the water-receptive conditions found in more pristine forested settings.

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Stormwater Retrofit of Highwood Estates Detention Basins to Enhance Water Quality Benefits

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Abstract

This paper presents the process used to identify water quality issues in an impaired watershed and the design and construction of stormwater basin retrofits to address the impairment issue.

A 2008 Watershed plan for Northfield Brook in Connecticut identified several water quality issues which lead to the impairment of the water quality in Northfield Brook Lake. The lake, which is under the jurisdiction of the Army Corps of Engineers, is closed many times during the year for recreational swimming uses due to excessive Escherichia coli (E.coli) concentrations. The E.coli concentrations routinely exceed the US EPA standard of the geometric mean of 5 samples over a 30 day period being less than 125 CFU/100 ml. While a direct source of the E.coli was not able to be determined, non-point source runoff from a medium density residential subdivision in Thomaston, CT was considered to be a potential source.

The subdivision is served by two detention basins which are non-functioning at the current time. Due to the lack of detention, the downstream channel has experienced significant gully erosion with the result of over 1,000 cubic yards of sediment being deposited into Northfield Brook Lake.

The Northwest Conservation District (NCD) applied for and received Section 319 funding from the CT Department of Environmental Protection (DEP) to address this impairment issue by hiring a consultant to design retrofits for the failing Highwood Estates stormwater basins. The goal of the retrofits was to increase the removal of coarse and fine sediments, on which E. Coli is commonly attached, and to reduce peak rates of runoff.

Watershed Track Down Survey

Northfield Brook is a stream that flows South through the Northfield section of Litchfield into Thomaston where it joins the Naugatuck River. Northfield Brook is an impaired stream that flows into the Department of Army Corps of Engineers (DOACE) Northfield Dam Flood Control Project in Thomaston, CT. The DOACE is experiencing problems of sediment build up (Figure 1) as well as elevated levels of nutrient concentration and bacteria within their facility near the toe of the watershed. As a result of these water quality degrading influences, the DOACE has been forced to close the swimming beach many times during most summers. They are even considering eliminating the pond altogether and allowing the stream to course through the project uncontrolled because of the unpredictable water quality problems.

The NCD conducted a visual track down survey assessment of the entire Northfield Brook watershed on and above the DOACE property to identify conditions responsible for the listed impairments. The goal of the track down survey was to collect information on all the possible causes of impairment and recommend and implement solutions in an effort to have the brook removed from the US EPA's "Impaired Waters of the US" list.

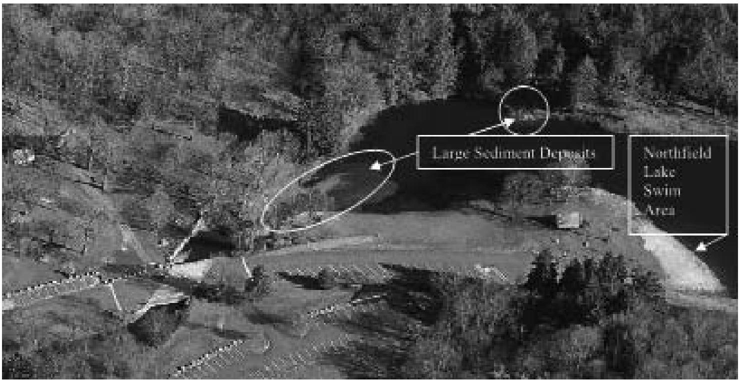

Figure 1 – Northfield Lake (NCD)

The Northfield Brook is identified by the CT DEP as Local Basin #6909. The watershed is approximately 4 miles long and 2 miles wide at the widest point between the top of the watershed and the Northfield Flood Control Dam. The watershed above the Northfield Brook Lake Dam is approximately 3,700 acres and has about 10 miles of associated perennial and intermittent streams. Most of the watershed is forested, with the balance being agricultural and residential development. Agricultural land use is mostly pasture with hay fields providing the dominant crop (Table 1).

Table 1 - Current Land Cover Classifications in the Northfield Brook Watershed

Developed	12%	Forested wetland	2%
Deciduous Forest	59%	Coniferous forest	5.5%
Other Grasses & Agriculture	18%	Barren	0.5%
Turf & Grass	1.5%	Utility ROW	1.5%

Track down surveys are conducted according to a modified version of the Unified Stream Assessment (USA) method developed for small urban watersheds by the Center for Watershed Protection. Eight Impact Assessment Forms record specific information about the condition and restorability of individual problem sites identified along the stream corridor. They include Stormwater Outfalls, Severe Erosion, Impacted Buffers, Utility Impacts, Trash and Debris, Stream Crossings, Channel Modification and Miscellaneous Impacts.

NCD staff worked with municipal officials in planning and conducting the surveys. This local knowledge and experience was very beneficial in identifying sources of impairments.

Water Quality Status

Currently the Northfield Brook is on the CT 2008 Impaired Waters list because at least one designated use cannot be supported, or at least one designated use is impaired. In the case of the Northfield Brook it is impaired for recreational use because of excessive E. Coli concentrations

Escherichia coli Concentration Sampling . The DOACE has been sampling for E. Coli (col/100ml) in the Northfield Lake continuously since 1995. The single sample maximum E. Coli concentration for a designated swimming area is 235 col/100ml. E. coli concentrations routinely exceed 235 col/100ml at the swimming area throughout most summers, resulting in frequent beach closures. Some samples contained well over 1000 col/100ml.

Phosphorus Concentration Sampling. The DOACE has been sampling for total phosphorus (ug/l) in the Northfield Lake since 1995. Lake water quality is quickly degraded with algae problems when phosphorus concentrations exceed 20 ug/l. Lake water sampling indicates that total phosphorus concentrations regularly exceed 20 ug/l with a few lake water samples exceeding 50 ug/l. High phosphorus concentrations have been evidenced by serious algae bloom problems during the summer and early fall.

Likely Sources of Non-Point Source Pollution

Stream Crossings . There are 27 stream crossings in the Northfield Brook Watershed. Most are stable but, the Knife Shop Road crossing is currently unstable and in danger of collapse, which would release hundreds of cubic yards of sediment into Northfield Lake.

Figure 2 - Failing Culverts (NCD)

Medium Density Residential Developments. There are several medium density developments in the watershed. Two in particular, Highwood Estates (Thomaston) & the Borough of Northfield (Litchfield) had tributary streams which were choked with filamentous algae. Non-point sources such as fertilizers, pet waste and failing septic systems are likely sources for these nutrient problems.

Stormwater Basins. The stormwater basins for the Highwood Estates in Thomaston have effectively failed. The design placed the inlet and outlet too close together, so “short circuiting” of the flow has occurred. The outlet control structures are too large to meter flows out, resulting in substantial increases of runoff volume leaving the basins every time it rains.

Figure 3 – Tributary with filamentous algae (NCD)

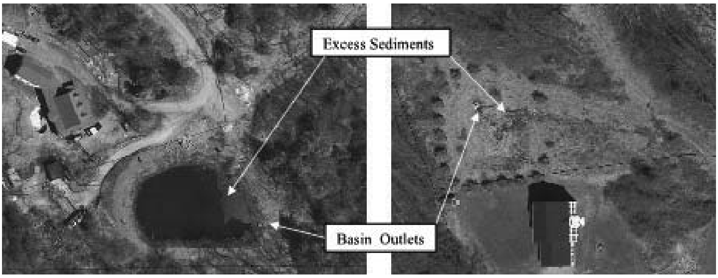

Figure 4 – Highwood Estates – Stormwater Basins (NCD)

The increased flows out of the basins have adversely impacted the natural receiving stream, which has resulted in the significant channel erosion shown in Figure 5. This eroded material has then created a sediment delta in Northfield Lake containing over 1,000 cubic yards of material. The sediment delta is shown in Figure 6.

Figure 5 – Gully Erosion from Failing Basin

Figure 6 – Sediment Deposition in Lake

Agricultural and Livestock Access. Reviewing aerial photographs showed that agricultural activities could also be partially responsible for the impairment in the watershed. A follow up visual assessment showed unfettered access for livestock to streams and riparian areas (Figure 7 below). Livestock access to stream channels causes the following types of Water Quality degradation:

- Destruction of the riparian vegetation,
- Erosion of the stream channel, banks, & riparian areas and the resultant in-stream sediment deposition,
- Introduction of nutrient loads from rich animal waste being carried into the stream by stormwater runoff,

- Pollutant loads from animal waste being directly deposited in the stream, and
- Degradation of stream channel stability and aquatic habitat.

Figure 7 – Livestock in stream and riparian area (NCD)

After evaluating all of the potential sources of pollutant loading in the Northfield Brook Watershed, it was determined that the failing stormwater basins in the Highwood Estates development were the largest single source of increased sediment & pollutant loading to Northfield Lake. The other potential sources were not ignored in this process. The unstable stream crossing was replaced with a bridge. The owners of the agricultural uses, particularly those with livestock uses were provided recommendations to prevent livestock from reaching the stream and riparian areas as well as funding sources from USDA.

Stormwater Basin Retrofits

NCD applied for and received 319 Funds to retain a consultant to design the retrofits for Highwood Estates basins. While the town owned the land surrounding both basins, the focus of the retrofits was to work within the existing footprint of the basins to affect a practical solution, yet minimize the potential cost of implementing the retrofit for the Town of Thomaston.

The first step was to inspect the basins in the field to observe the conditions in person. The smaller basin was completely non-functional with any runoff quickly entering and leaving the basin, neither detention or water quality treatment was being provided.

A survey with topographic information was obtained to provide the necessary base information for design purposes. After the survey was done, it was time to analyze the contributing watershed areas in order to design the retrofits.

Small Basin

Existing Conditions. The small basin has a 24.5 acre watershed area consisting of residential roads and ½ acre building lots. The basin consists of a small, elliptical footprint with the outlet structure located at the north end of the basin. Runoff is directed to the northeast corner of the basin by a riprap swale which conveys the runoff from the road drainage system. Due to the proximity of the inlet and outlet to each other, the runoff has cut a direct path between the two points, resulting in most of the basin not being used.

The peak rate of runoff for a 2-year storm was calculated by the HydroCAD model. Approximately 30.09 cfs is directed to the basin during this storm event. In addition, the Water Quality Volume (WQV) as found in the CT DEP 2004 Stormwater Quality Manual (Manual) was determined for the watershed. A total of 35,278 cubic feet of storage volume would need to be provided for the small basin to achieve this goal.

Retrofit Design Due to site constraints, the retrofit options were limited for this basin. First, a well-defined depressed forebay was created above the existing basin. The forebay provides 2,568 cubic feet of storage volume (7.3% of the WQV, the goal is to have 10%). The riprap swale was redirected to direct runoff into the east end of the forebay with the outlet being located at the western end. The forebay is slightly over four feet in depth. This is important as to minimize the resuspension of fine sediments in the forebay during subsequent runoff events.

The basin itself was excavated to provide a single, deep pool feature six feet in depth. A vegetated, aquatic shelf was created along the perimeter of the deep pool. The single outlet pipe was replaced with a staged orifice outlet design to provide a slight reduction of the peak rate of runoff in the basin above the permanent pool. The peak rate of runoff for the 2-year event will be reduced from 30.09 cfs to 28.87 cfs.

The regraded basin and new forebay provide a total of 5,278 cubic feet of fixed volume for water quality purposes. This is approximately 15% of the calculated WQV, but is the maximum available based upon site limitations. The features of the basin retrofit are shown in Figure 8.

Large Basin

Existing Conditions The large basin has a 28.32 acre watershed area consisting of residential roads and ½ acre building lots. The basin is approximately circular in shape. The inlet swale enters the basin in the northeast portion, while the outlet structure is located at the southeastern end. Similar to the small basin, runoff short circuits the storage area of the basin and makes a quick line in and out. The outlet control structure consists of a square 18” x 18” opening which does not provide any measure of rate reduction.

The peak rate of runoff for a 2-year storm was calculated. Approximately 30.66 cfs is directed to the basin during this storm event. In addition, the Water Quality Volume (CT DEP 2004 Stormwater Quality Manual) was determined for the watershed. A total of 41,810 cubic feet of storage volume would need to be provided for the large basin.

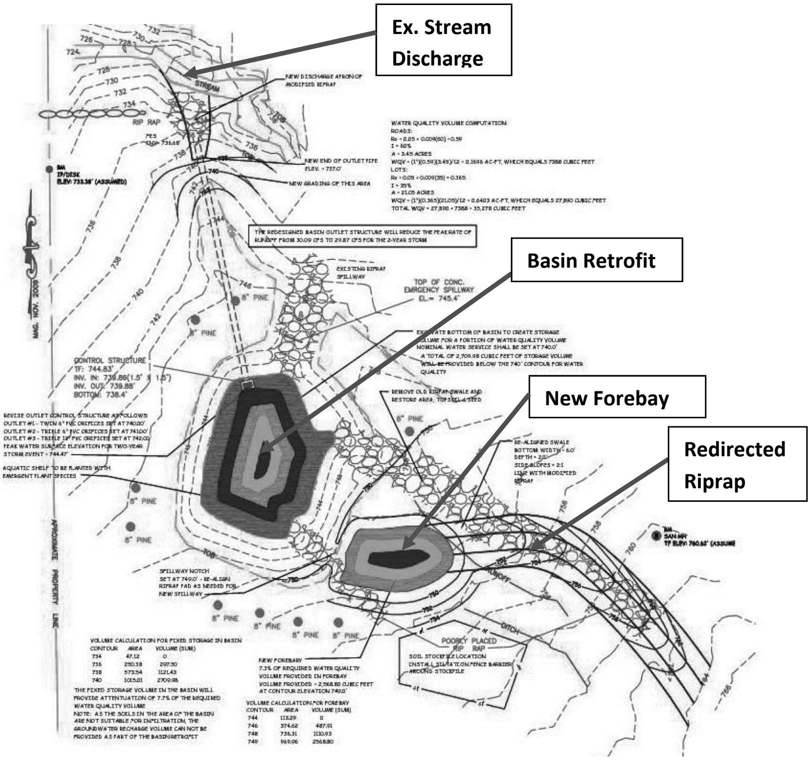

Figure 8 – Small Basin Retrofit (Trinkaus Engineering, LLC)

Retrofit Design There is more space available for this basin retrofit. A large, separate forebay was constructed above and north of the existing basin. This forebay is six feet in depth and provides a fixed storage volume of 5,285 cubic feet. This is approximately 12.6% of the required WQV which is more than the suggested 10% of the WQV for a forebay under the Manual.

The flow from the existing riprap swale was directed into the forebay at the east, with the outlet from the forebay being on the western end. A new riprap swale will direct runoff from the forebay to the northwest corner of the basin.

The larger basin size allowed for a more significant retrofit to be implemented compared to the smaller basin. A two (2) foot micro-pool was placed at the inlet of the new riprap swale. A second, deeper micro-pool was created just before the existing outlet control structure. A low flow path was created from the shallow micro-pool to the deeper one in a circuitous path.

The majority of the basin bottom will be planted to create a shallow marsh environment. Two areas will be raised by 6" to create high marsh areas which will encourage a low, slow flow path for runoff within the basin as well as maximizing the contact time between stormwater and the vegetation. A total of 17,996 cubic feet of fixed volume is provided between the forebay and permanent pool in the basin, which is approximately 43% of the required WQV.

The outlet structure was modified to create a staged orifice system. Due to the size of this basin, the 2-year peak rate of runoff will be reduced from 30.66 cfs to 5.00 cfs. This is a substantial reduction that will prevent the further erosion of the existing stream channel between the basin and Northfield Lake.

The redesigned basin is shown in Figure 9.

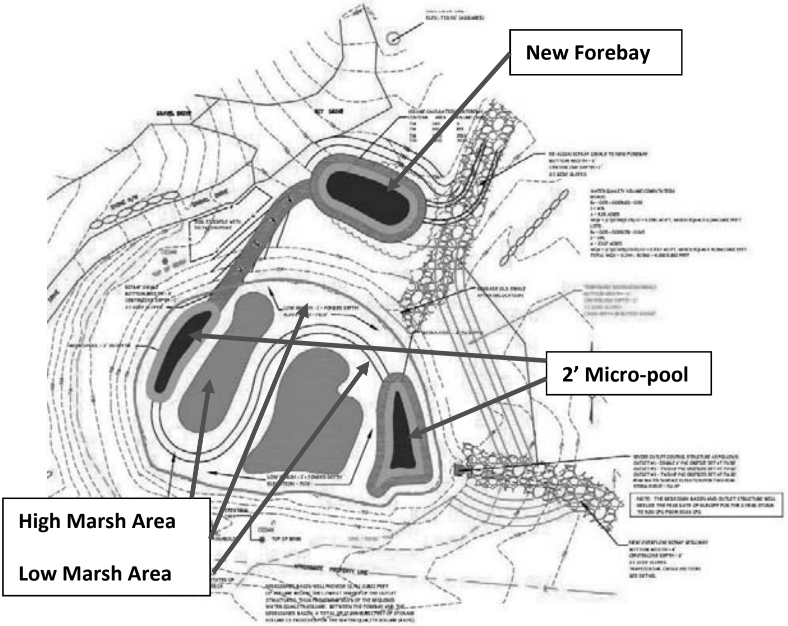

Figure 9 – Large Basin Retrofit (Trinkaus Engineering, LLC)

Pollutant Renovation Analysis

The Simple Method was used to calculate the estimated pollutant loads from the contributing watershed area for each basin on an annual basis. The effectiveness of the stormwater management system for each basin was evaluated for removal of TSS, TP, TN, Zn, TPH and DIN. Removal efficiencies for the various treatment systems were taken from both University of New Hampshire Stormwater Center and the ASCE BMP Database.

Table 2 – Results of Simple Method and Treatment System Evaluation

Small Basin						
	TSS	**TP**	**TN**	**Zn**	**TPH**	**DIN**
Current (lbs)	**6872**	**29.2**	**215.9**	**17.3**	**163**	**35.3**
With-Treatment (lbs)	**302.6**	**17.2**	**57.6**	**0.2**	**18.6**	**16.2**
% Removal	**95.6**	**41.1**	**73.3**	**98.8**	**88.6**	**54.1**

It can be seen by the modeling results that sediment loads will be substantially reduced by these basin retrofits and thus bacteria concentrations will also be reduced due to their affinity to attach to sediment particles.

Table 3 – Results of Simple Method and Treatment System Evaluation

Large Basin						
	TSS	**TP**	**TN**	**Zn**	**TPH**	**DIN**
Current (lbs)	**8422**	**34.2**	**257.3**	**20.4**	**205.6**	**42.1**
With-Treatment (lbs)	**264.9**	**10.8**	**97**	**0.8**	**137.7**	**15.6**
% Removal	**96.9**	**68.4**	**62.3**	**96.1**	**33.0**	**63.0**

Implementation

As of the spring of 2012, the Town of Thomaston is soliciting bids from contractors to construct the basin retrofits by September. The goal is to have the retrofits completed prior to fall of 2012.

Conclusion

The retrofits of these two storm water basins will provide a measurable improvement to stormwater quality which will ultimately reach Northfield Lake. In addition, the cost of implementing these retrofits by the Town of Thomaston was minimized by working with the natural conditions to the maximum extent possible.

The approaches and concepts used in these retrofits can easily apply to other stormwater basins to increase the benefits of old standard detention basins.

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